EE C247B – ME C218
Introduction to MEMS Design
Spring 2020

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Lecture Module 5: Surface Micromachining

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Lecture Outline

- Reading: Senturia Chpt. 3, Jaeger Chpt. 11, Handout: "Surface Micromachining for Microelectromechanical Systems"
- Lecture Topics:
  - Polysilicon surface micromachining
  - Stiction
  - Residual stress
  - Topography issues
  - Nickel metal surface micromachining
  - 3D "pop-up" MEMS
  - Foundry MEMS: the "MUMPS" process
  - The Sandia SUMMIT process

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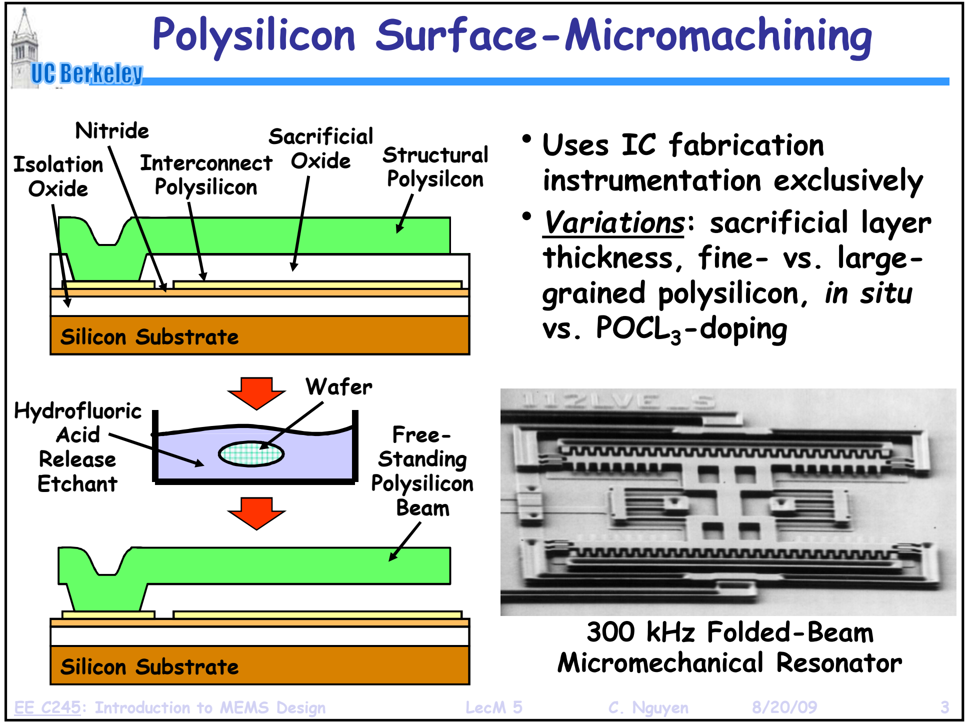

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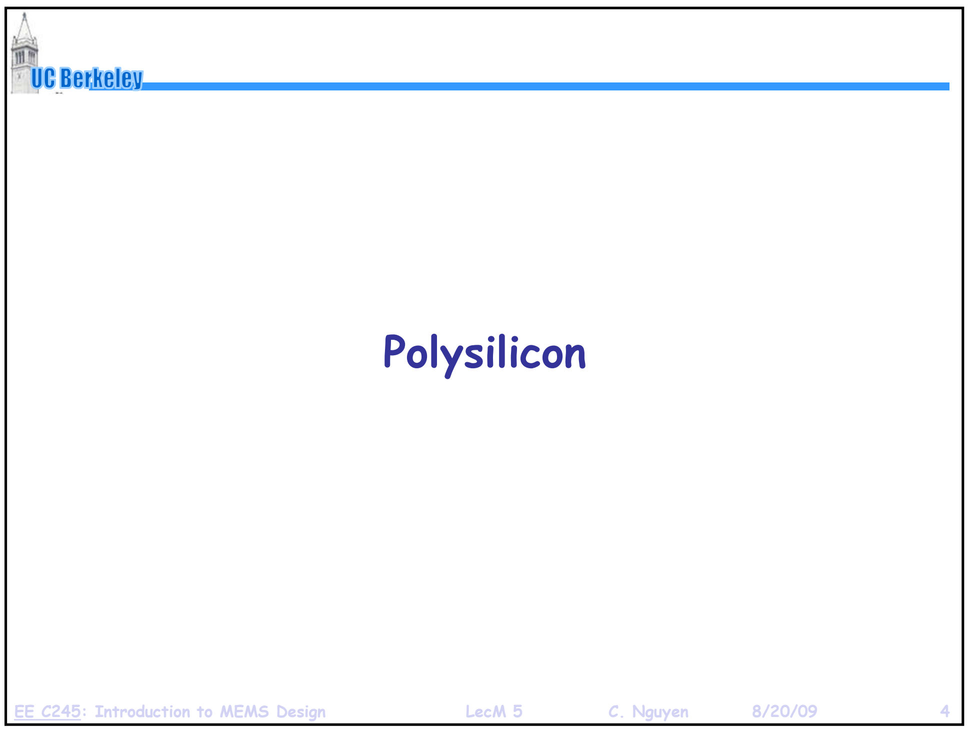

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Why Polysilicon?

- Compatible with IC fabrication processes
  - Process parameters for gate polysilicon well known
  - Only slight alterations needed to control stress for MEMS applications
- Stronger than stainless steel: fracture strength of polySi ~ 2-3 GPa, steel ~ 0.2GPa-1GPa
- Young's Modulus ~ 140-190 GPa
- Extremely flexible: maximum strain before fracture ~ 0.5%
- Does not fatigue readily

- Several variations of polysilicon used for MEMS
  - LPCVD polysilicon deposited undoped, then doped via ion implantation, PSG source, $POCl_3$, or B-source doping
  - In situ-doped LPCVD polysilicon
  - Attempts made to use PECVD silicon, but quality not very good (yet) → etches too fast in HF, so release is difficult

Polysilicon Surface-Micromachining Process Flow

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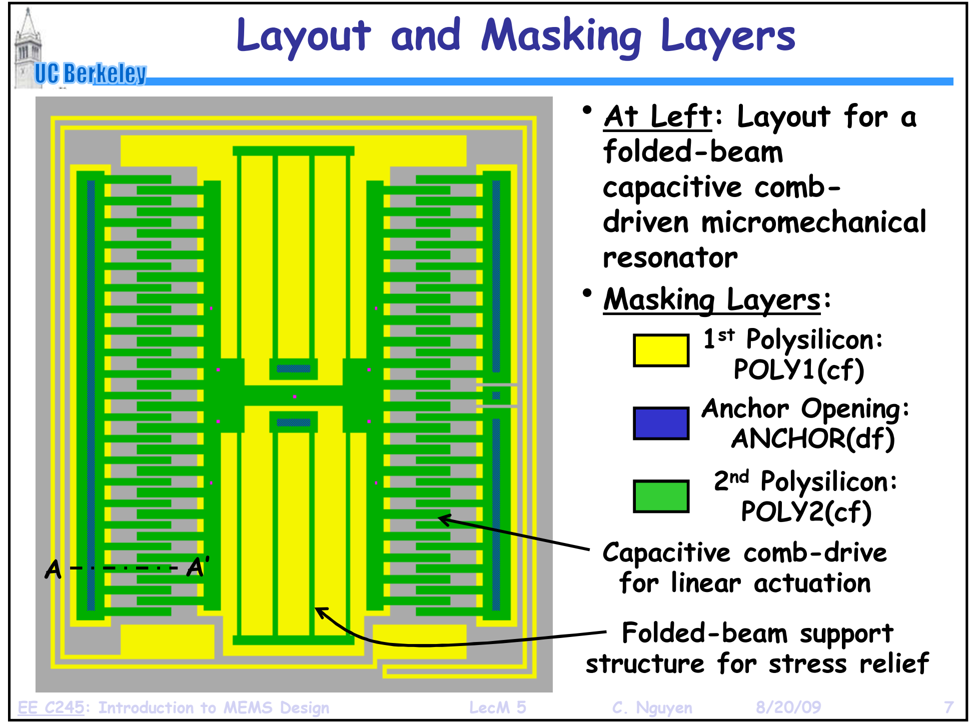

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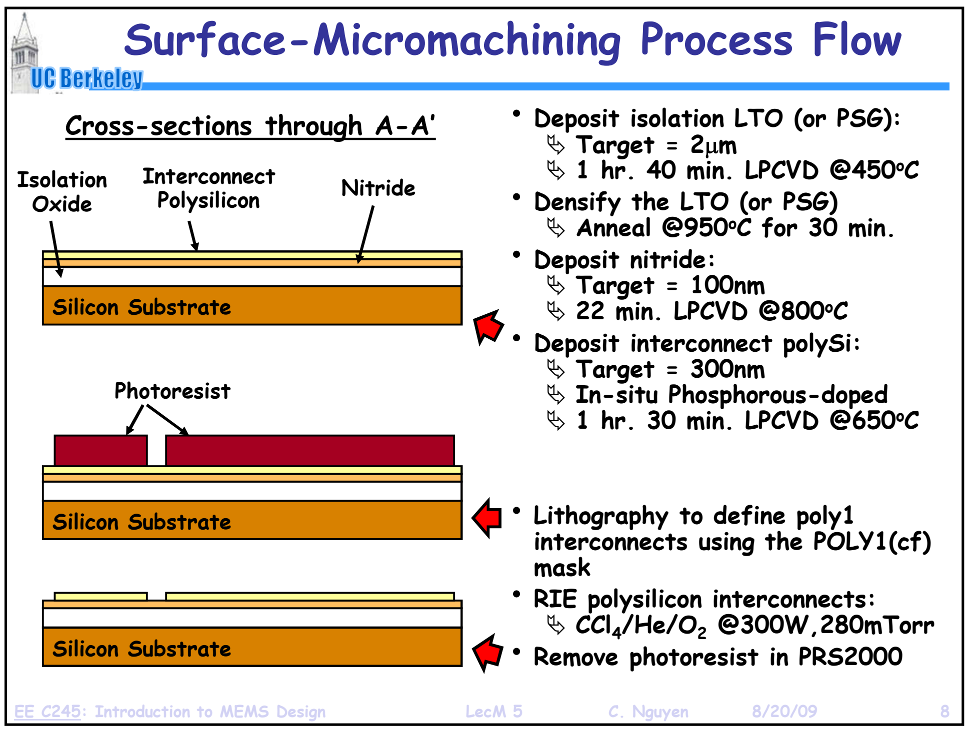

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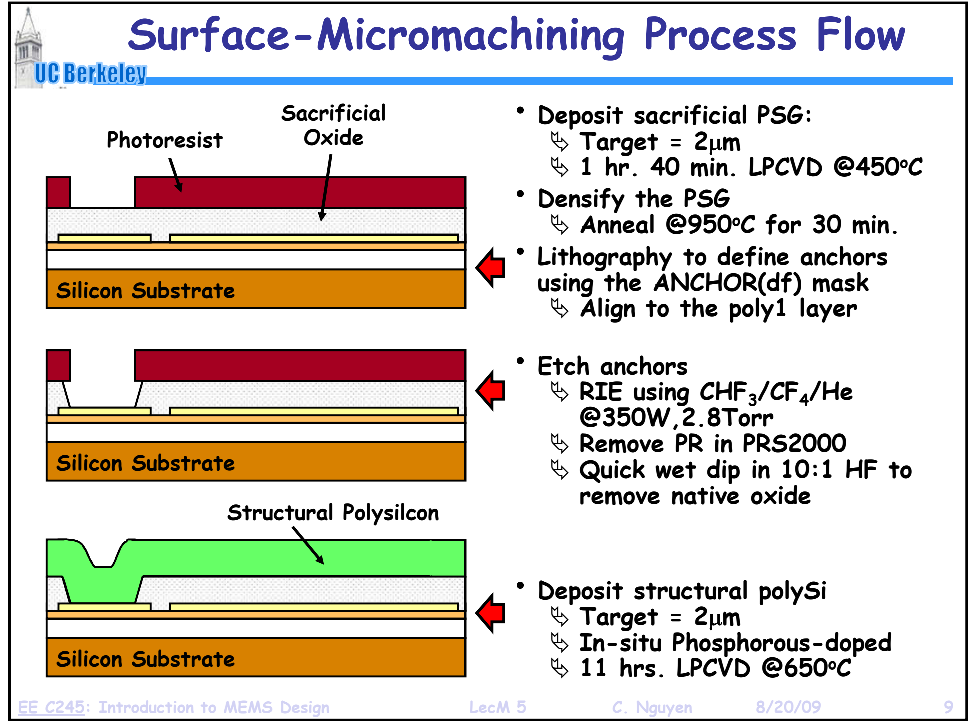

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Surface-Micromachining Process Flow

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Oxide Hard Mask

Silicon Substrate

- Deposit oxide hard mask
  - Target = 500nm
  - 25 min. LPCVD @450°C
- Stress Anneal
  - 1 hr. @ 1050°C
  - Or RTA for 1 min. @ 1100°C in 50 sccm N_2
- Lithography to define poly2 structure (e.g., shuttle, springs, drive & sense electrodes) using the POLY2(cf) mask
  - Align to the anchor layer
  - Hard bake the PR longer to make it stronger
- Etch oxide mask first
  - RIE using $CHF_3/CF_4/He$ @350W,2.8Torr
- Etch structural polysilicon
  - RIE using $CCl_4/He/O_2$ @300W,280mTorr
  - Use 1 min. etch/1 min. rest increments to prevent excessive temperature

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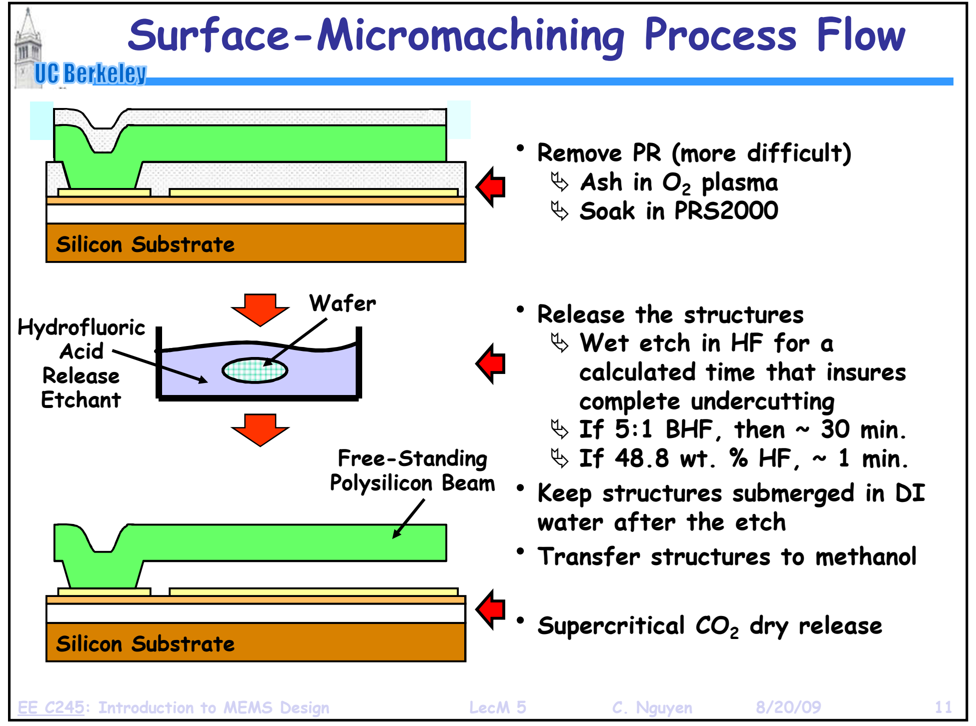

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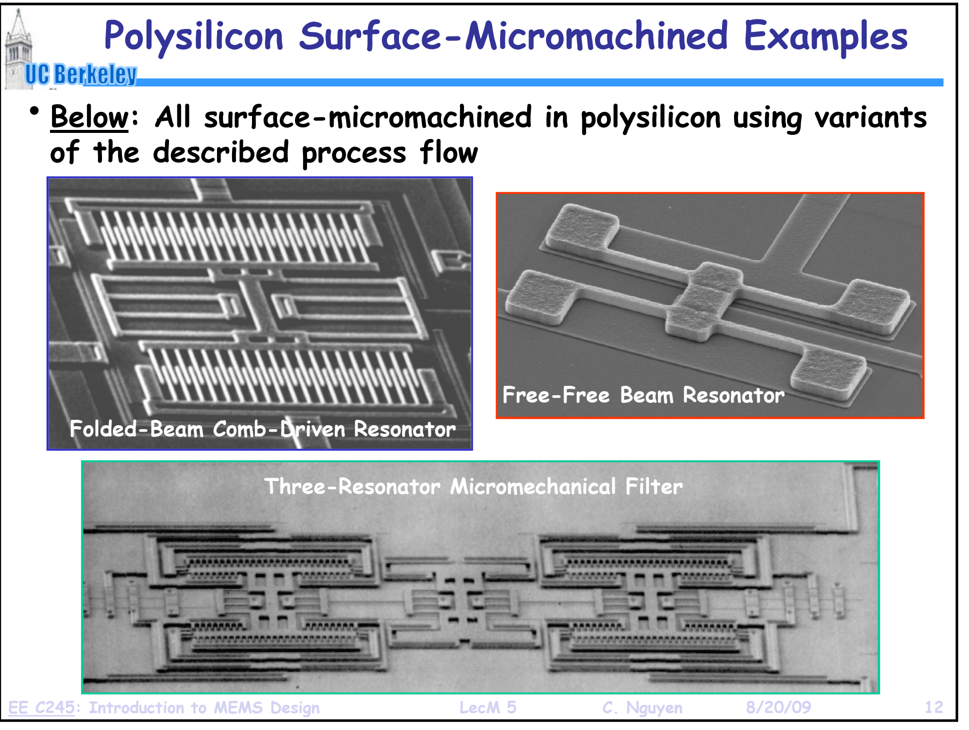

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Structural/Sacrifical Material Combinations

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Structural Material	Sacrificial Material	Etchant
Poly-Si	SiO_2, PSG, LTO	HF, BHF
Al	Photoresist	O_2 plasma
SiO_2	Poly-Si	XeF_2
Al	Si	TMAH, XeF_2
Poly-SiGe	Poly-Ge	H_2O_2, hot H_2O

- Must consider other layers, too, as release etchants generally have a finite E.R. on any material
- Ex: concentrated HF (48.8 wt. %)
  - Polysilicon E.R. ~ 0
  - Silicon nitride E.R. ~ 1-14 nm/min
  - Wet thermal SiO_2 ~ 1.8-2.3 μm/min
  - Annealed PSG ~ 3.6 μm/min
  - Aluminum (Si rich) ~ 4 nm/min (much faster in other Al)

Wet Etch Rates (f/ K. Williams)

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Wet-Etch Rates for Micromachining and IC Processing (Å/min)

The top etch rate was measured by the authors with fresh solutions, etc. The center and bottom values are the low and high etch rates observed by the authors and others in our lab under less carefully controlled conditions.

ETCHANT EQUIPMENT CONDITIONS	TARGET MATERIAL	MATERIAL SC Si <100>	Poly n+	Poly undop	Wet Ox	Dry Ox	LTO undop	PSG unanl	PSG annld	Stoic Nitrid	Low-σ Nitrid	Al/ 2% Si	Sput Tung	Sput Ti	Sput Ti/W	OCG 820PR	Olin HntPR
Concentrated HF (49%) Wet Sink Room Temperature	Silicon oxides	-	0	-	23k 18k 23k	F	>14k	F	36k	140	52 30 52	42 0 42	<50	F	-	P 0	P 0
10:1 HF Wet Sink Room Temperature	Silicon oxides	-	7	0	230	230	340	15k	4700	11	3	2500 2500 12k	0	11k	<70	0	0
25:1 HF Wet Sink Room Temperature	Silicon oxides	-	0	0	97	95	150	W	1500	6	1	W	0	-	-	0	0
5:1 BHF Wet Sink Room Temperature	Silicon oxides	-	9	2	1000 900 1080	1000	1200	6800	4400 3500 4400	9	4 3 4	1400	<20 0.25 20	F	1000	0	0
Phosphoric Acid (85%) Heated Bath with Reflux 160°C	Silicon nitrides	-	7	-	0.7	0.8	<1	37	24 9 24	28 28 42	19 19 42	9800	-	-	-	550	390
Silicon Etchant (126 HNO_3 : 60 H_2O : 5 NH_4F) Wet Sink Room Temperature	Silicon	1500	3100 1200 6000	1000	87	W	110	4000	1700	2	3	4000	130	3000	-	0	0
KOH (1 KOH : 2 H_2O by weight) Heated Stirred Bath 80°C	<100> Silicon	14k	>10k	F	77 41 77	-	94	W	380	0	0	F	0	-	-	F	F
Aluminum Etchant Type A (16 H_3PO_4 : 1 HNO_3 : 1 HAc : 2 H_2O) Heated Bath 50°C	Aluminum	-	<10	<9	0	0	0	-	<10	0	2	6600 2600 6600	-	0	-	0	0
Titanium Etchant (20 H_2O : 1 H_2O_2 : 1 HF) Wet Sink Room Temperature	Titanium	-	12	-	120	W	W	W	2100	8	4	W	0 0 <10	8800	-	0	0
H_2O_2 (30%) Wet Sink Room Temperature	Tungsten	-	0	0	0	0	0	0	0	0	0	<20	190 190 1000	0	60 60 150	<2	0
Piranha (~50 H_2SO_4 : 1 H_2O_2) Heated Bath 120°C	Cleaning off metals and organics	-	0	0	0	0	0	-	0	0	0	1800	-	2400	-	F	F
Acetone Wet Sink Room Temperature	Photoresist	-	0	0	0	0	0	-	0	0	0	0	-	0	-	>44k	>39k

Notation: - =test not performed; W=not performed, but known to Work (≥ 100 Å/min); F=not performed, but known to be *Fast* (≥ 10 kÅ/min); P=some of film *Peeled* during etch or when rinsed; A=film was visibly *Attacked* and roughened.
Etch areas are all of a 4-inch wafer for the transparent films and half of the wafer for single-crystal silicon and the metals.
Etch rates will vary with temperature and prior use of solution, area of exposure of film, other materials present (e.g., photoresist), film impurities and microstructure, etc. *Some variation should be expected.*

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Film Etch Chemistries

- For some popular films:

Material	Wet etchant	Etch rate [nm/min]	Dry etchant	Etch rate [nm/min]
Polysilicon	HNO_3:H_2O:NH_4F	120-600	SF_6 + He	170-920
Silicon nitride	H_3PO_4	5	SF_6	150-250
Silicon dioxide	HF	20-2000	CHF_3 + O_2	50-150
Aluminum	H_3PO_4:HNO_3:CH_3COOH	660	Cl_2 + $SiCl_4$	100-150
Photoresist	Acetone	>4000	O_2	35-3500
Gold	KI	40	n/a	n/a

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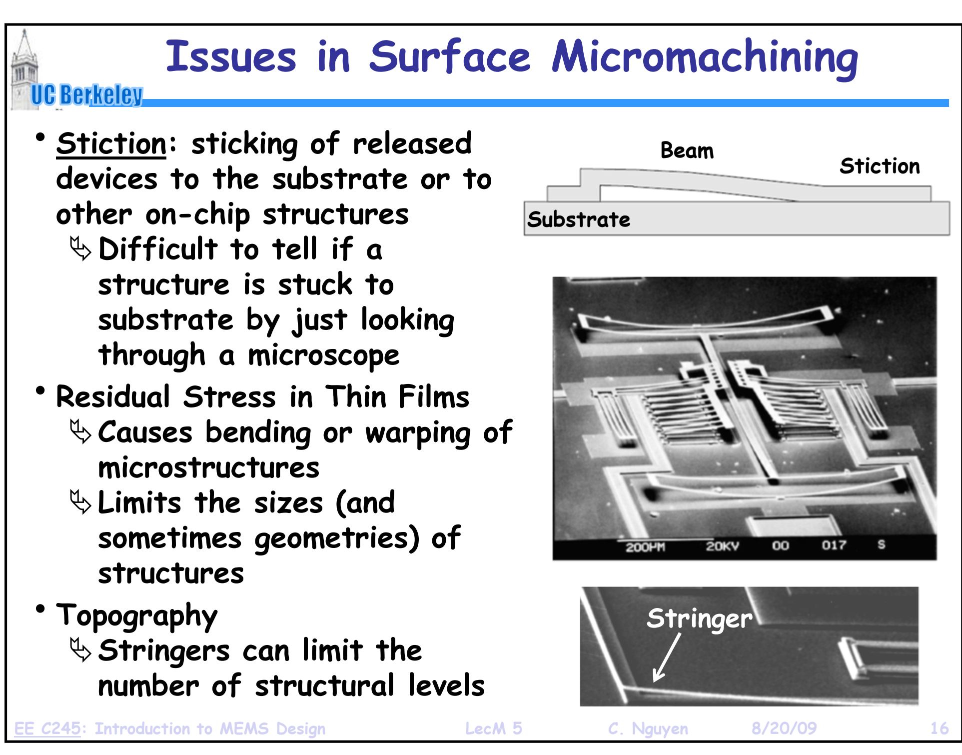

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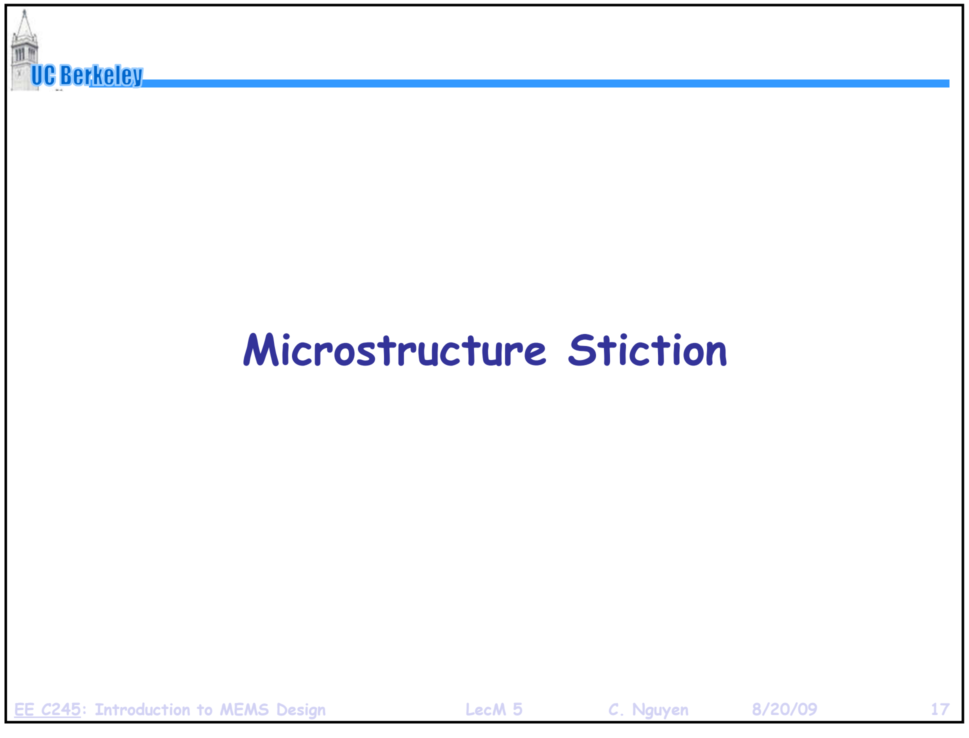

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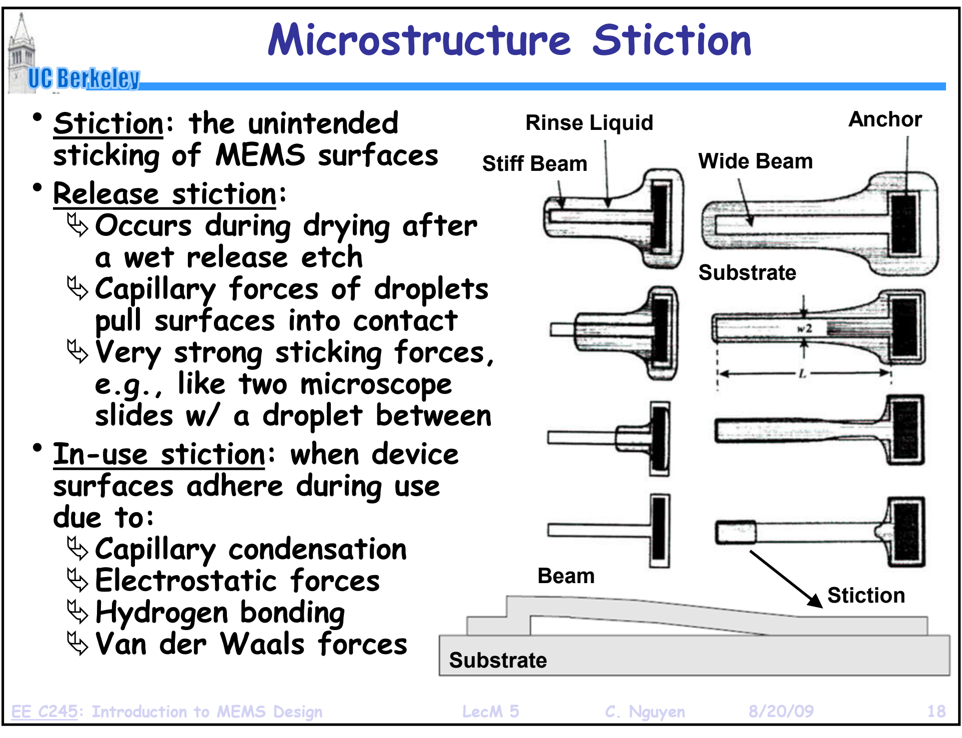

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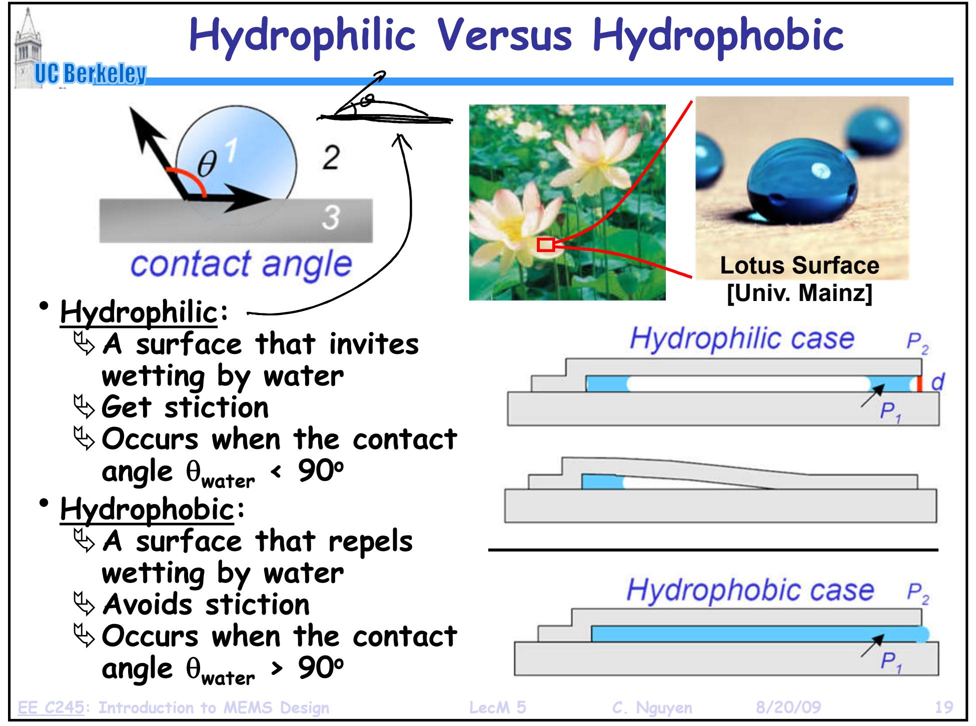

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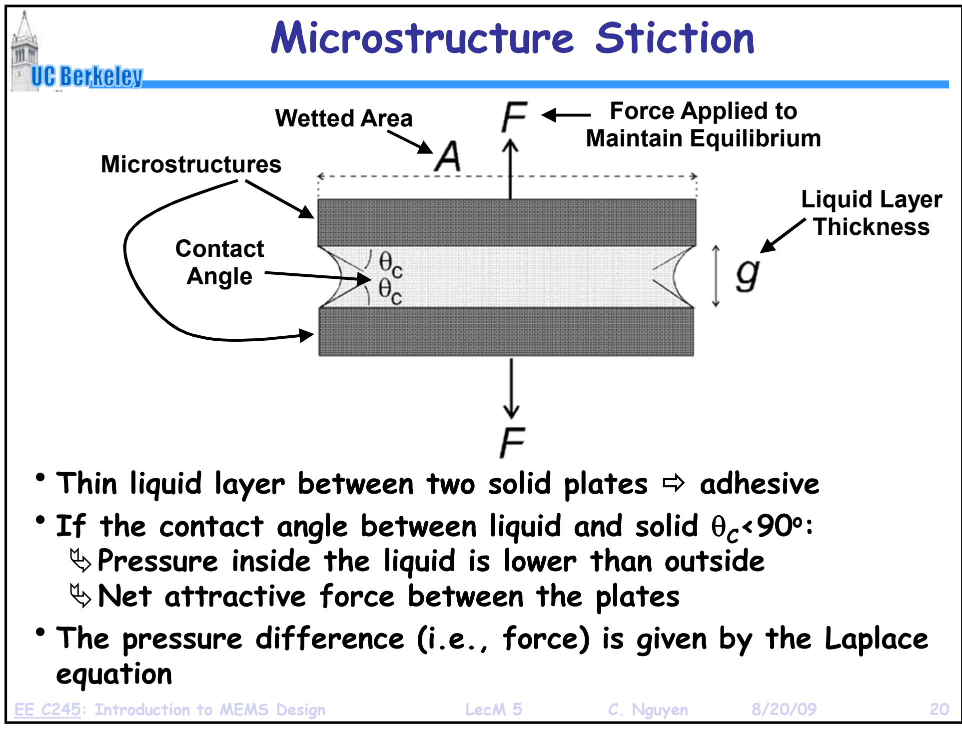

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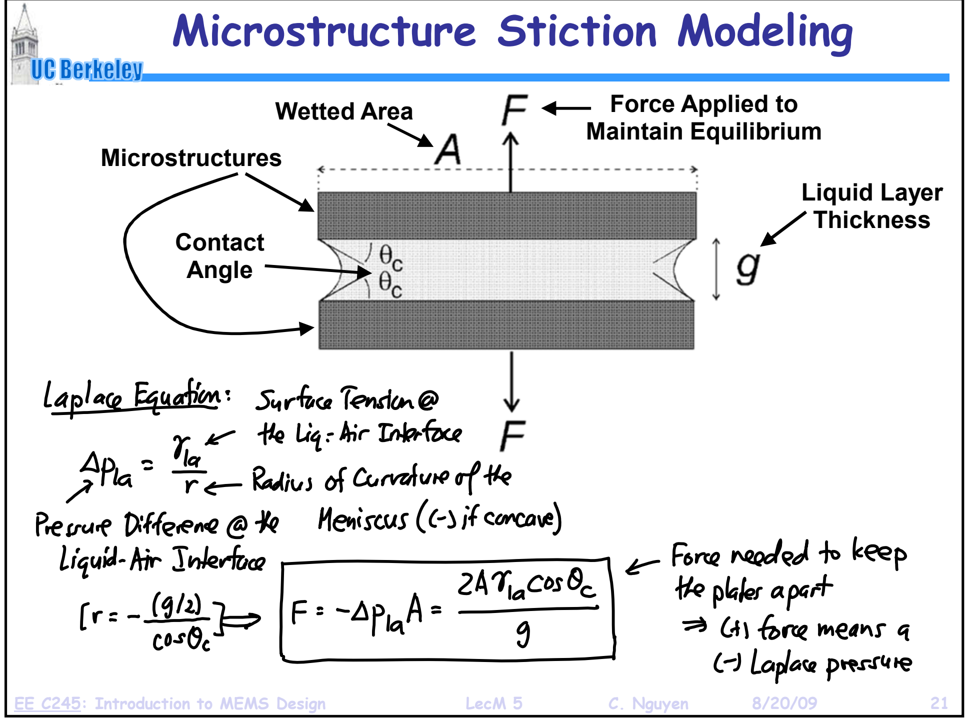

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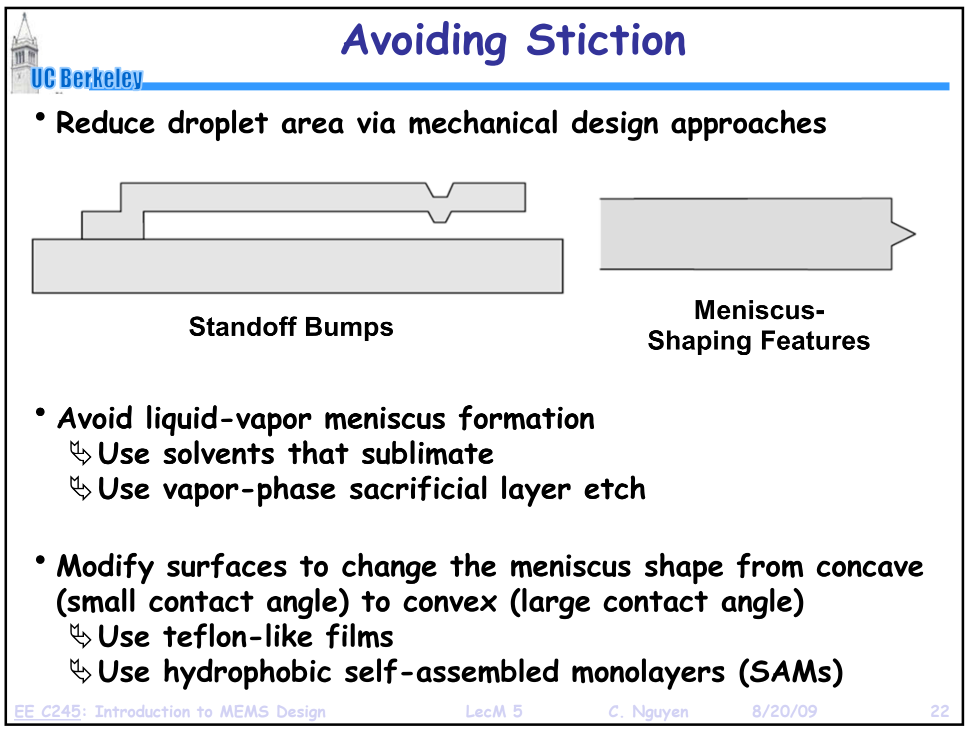

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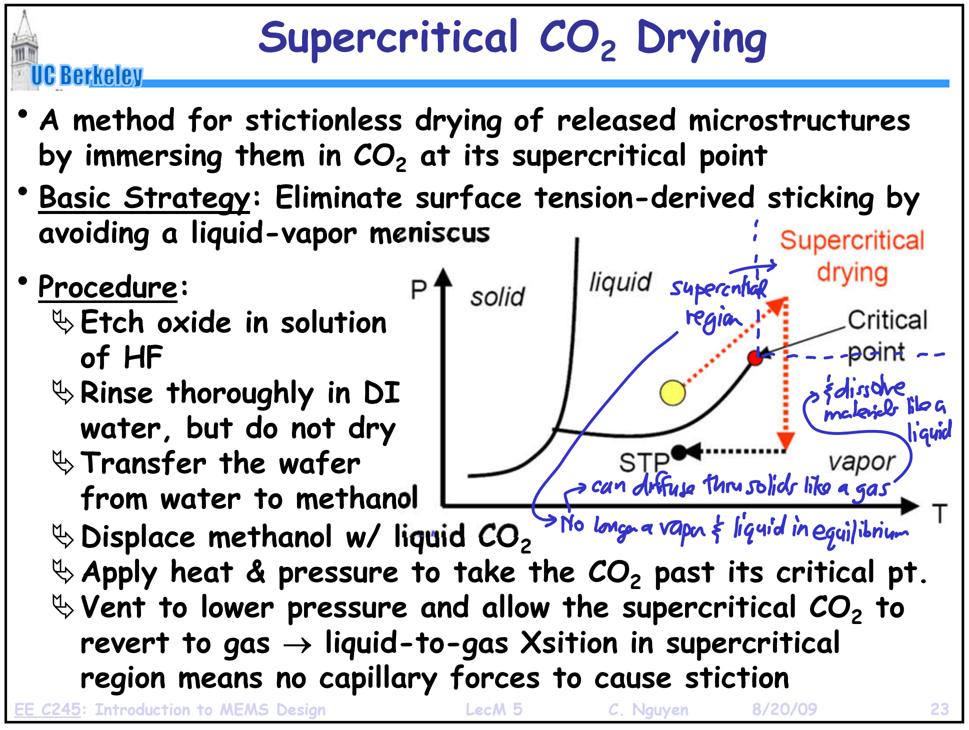

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Hydrophilic Versus Hydrophobic

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θ 1 2 3

contact angle

Lotus Surface [Univ. Mainz]

- Hydrophilic:
  - A surface that invites wetting by water
  - Get stiction
  - Occurs when the contact angle θ_{water} < 90°
- Hydrophobic:
  - A surface that repels wetting by water
  - Avoids stiction
  - Occurs when the contact angle θ_{water} > 90°

Hydrophilic case P_2 d P_1

Hydrophobic case P_2 P_1

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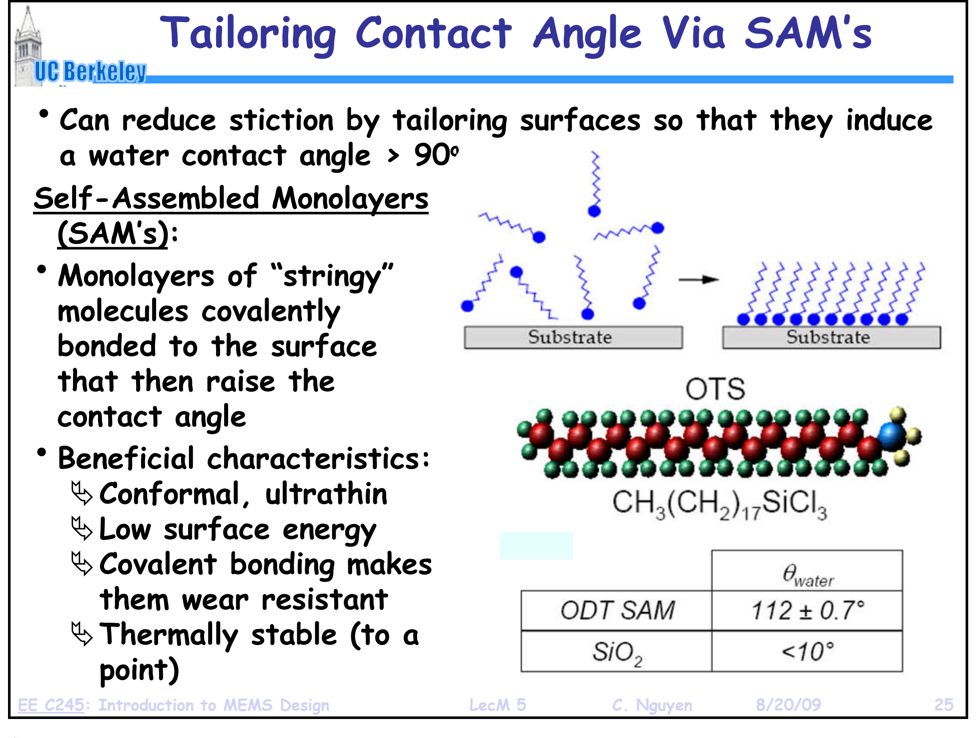

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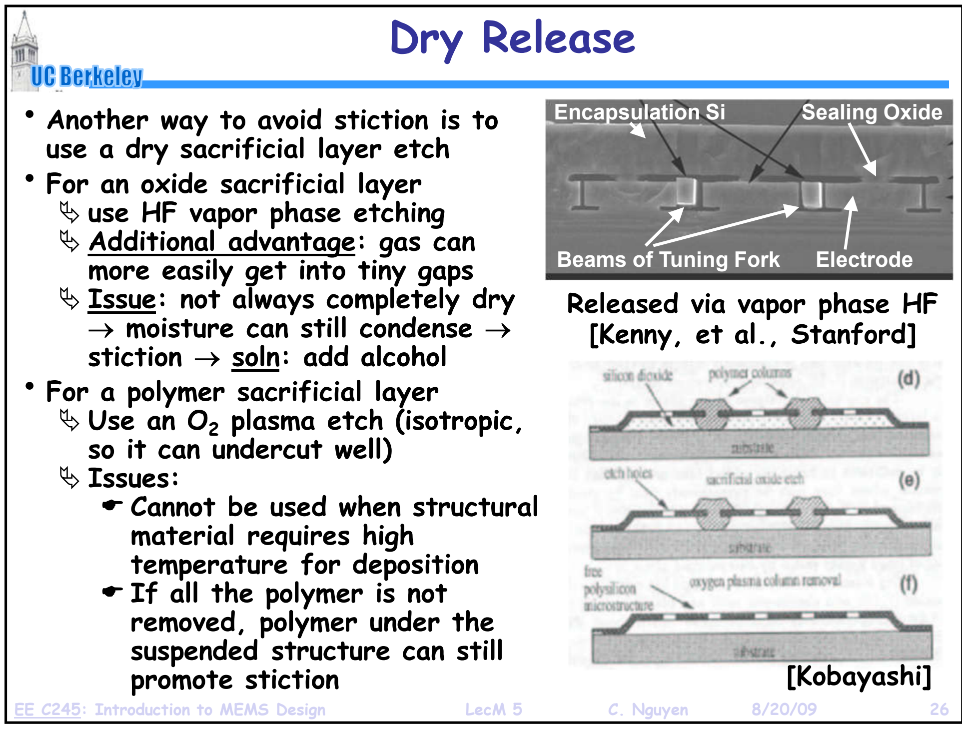

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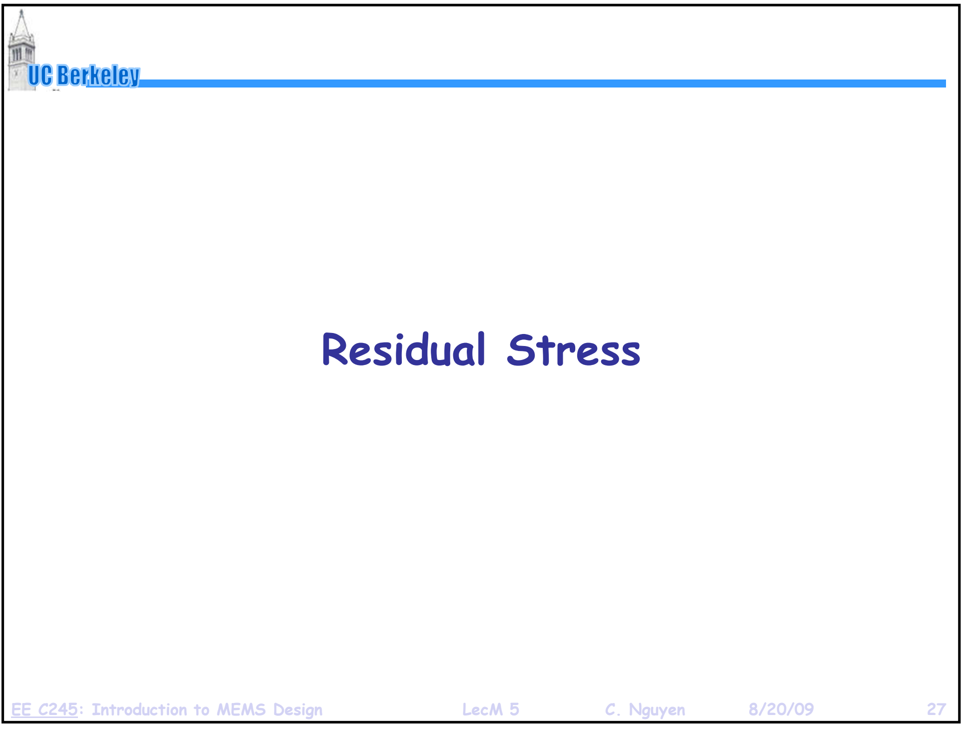

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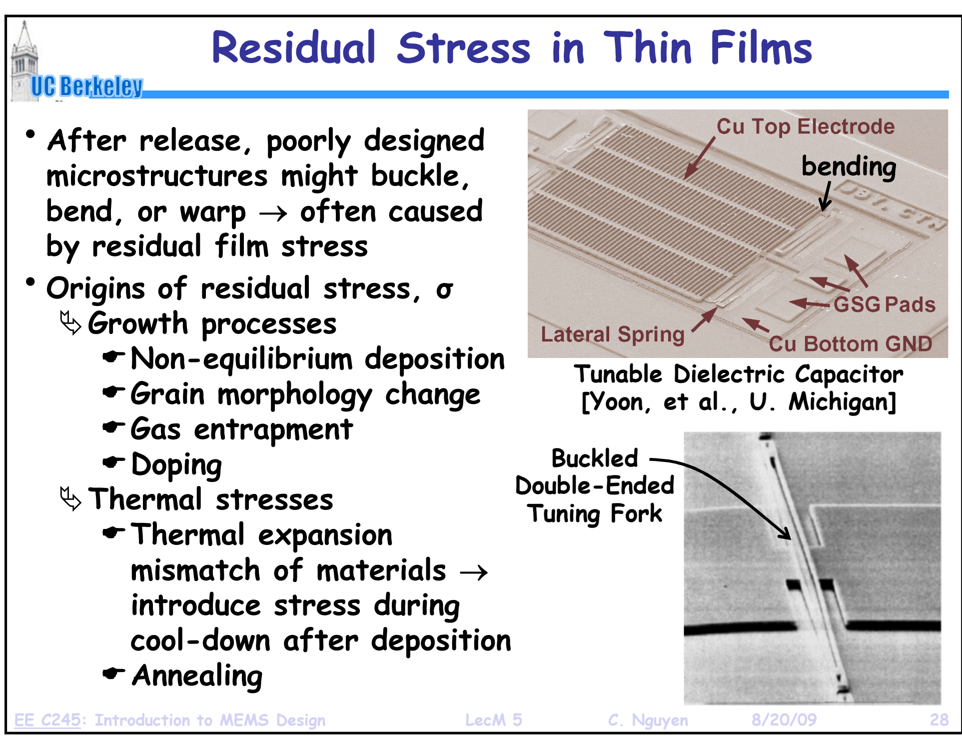

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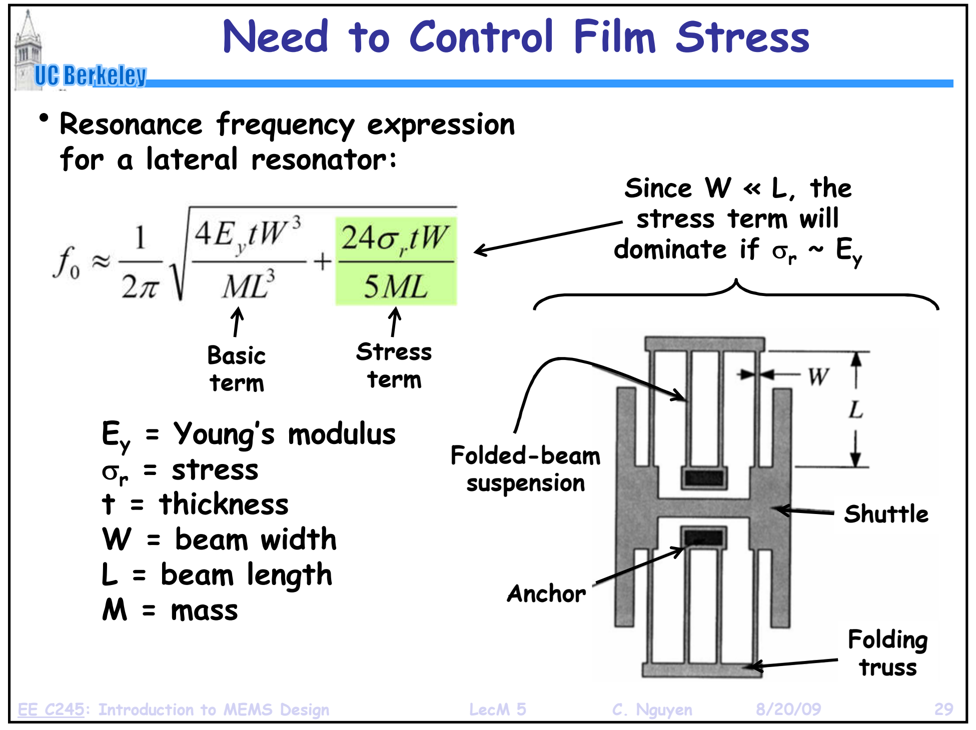

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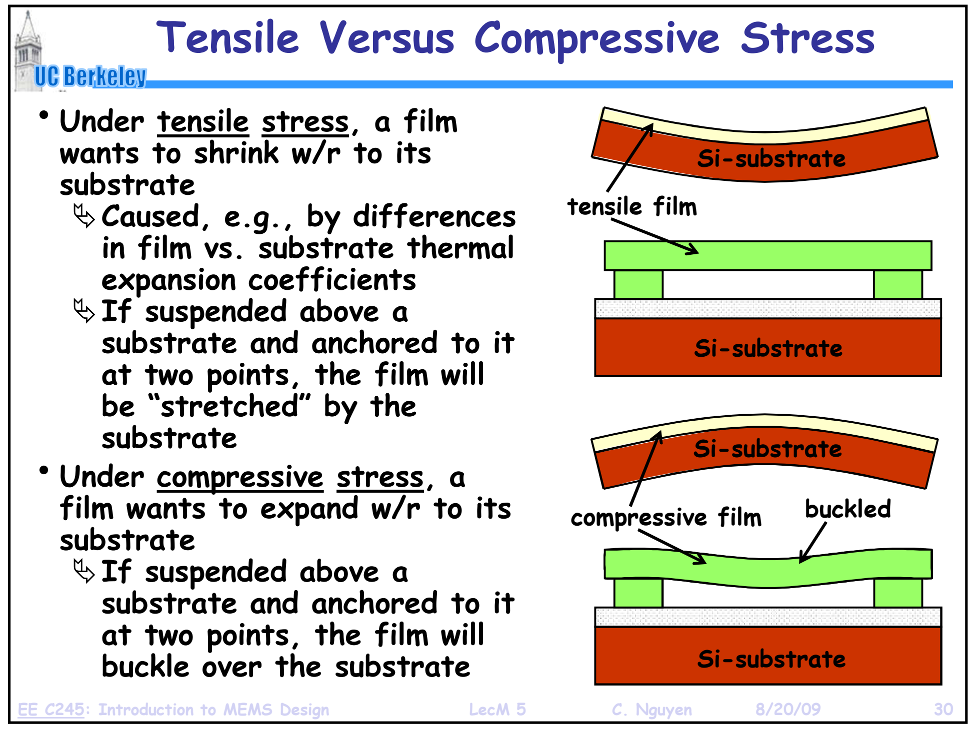

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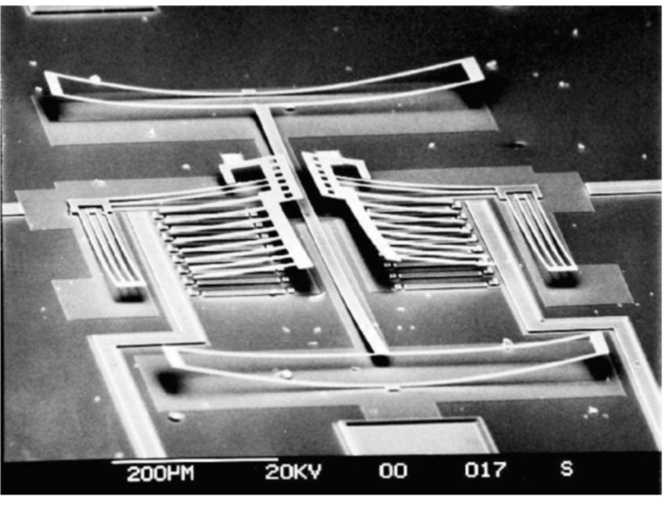
Vertical Stress Gradients

- Variation of residual stress in the direction of film growth
- Can warp released structures in z-direction



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Stress in Polysilicon Films

- Stress depends on crystal structure, which in turn depends upon the deposition temperature
- Temperature ≤ 600°C
  - ↳ Films are initially amorphous, then crystallize
  - ↳ Get equiaxed crystals, largely isotropic
  - ↳ Crystals have higher density → tensile stress
  - ↳ Small stress gradient
- Temperature ≥ 600°C
  - ↳ Columnar crystals grow during deposition
  - ↳ As crystals grow vertically and in-plane they push on neighbors → compressive stress
  - ↳ Positive stress gradient

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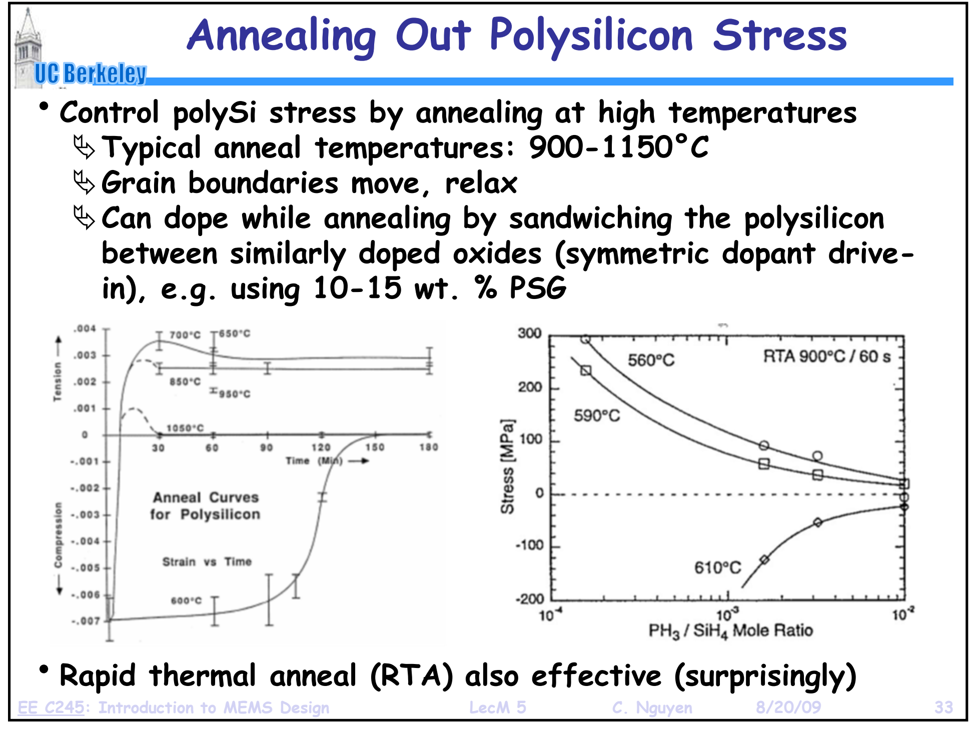

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Topography Issues

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- Degradation of lithographic resolution
  - PR step coverage, streaking

PR

Thickness differences pose problems for reduction steppers

Direction of Spin

PR

PR

- Stringers
  - Problematic when using anisotropic etching, e.g., RIE

RIE

Stringer

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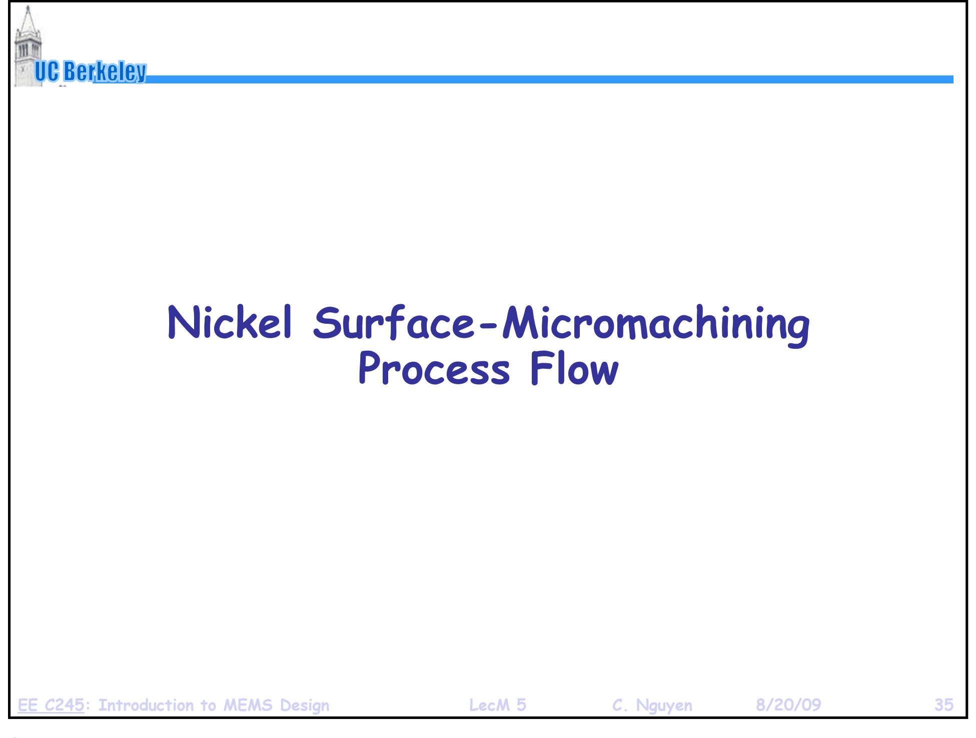

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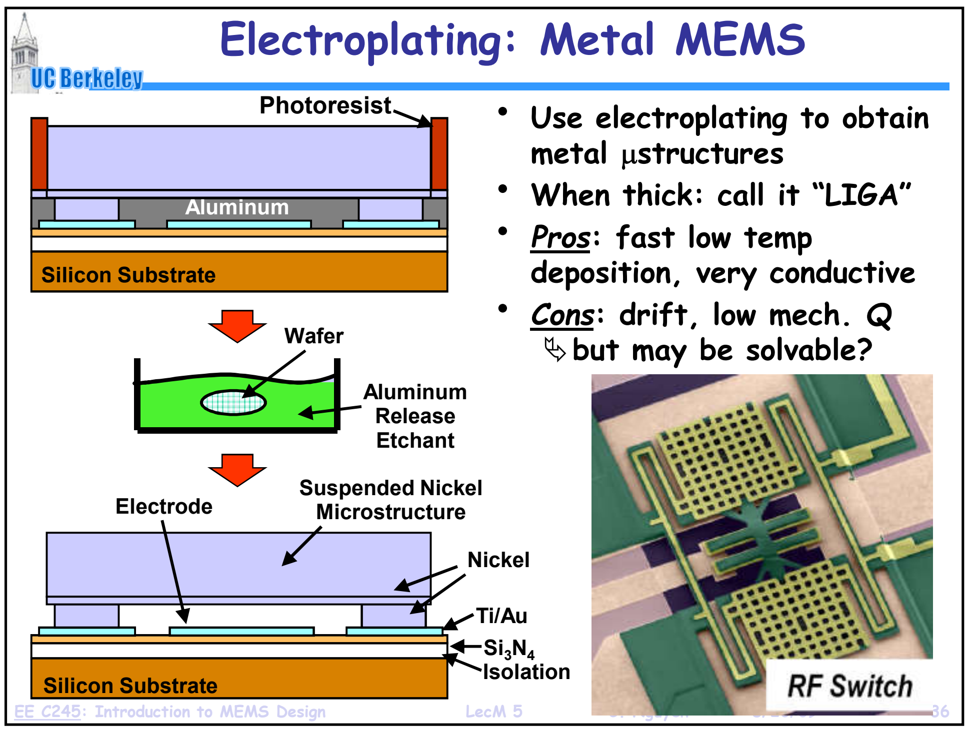

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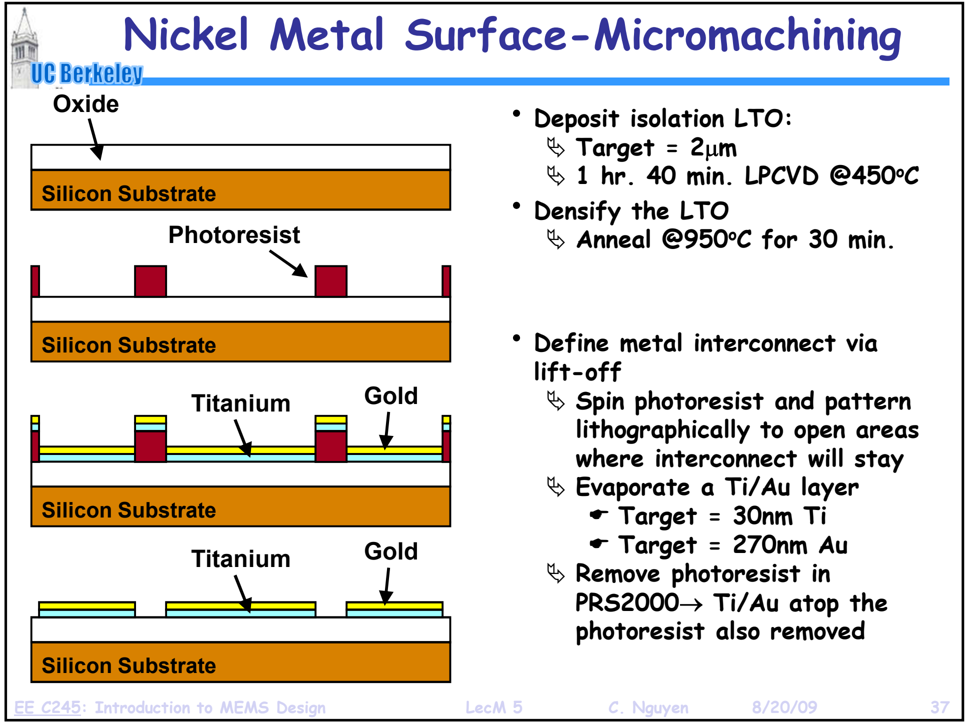

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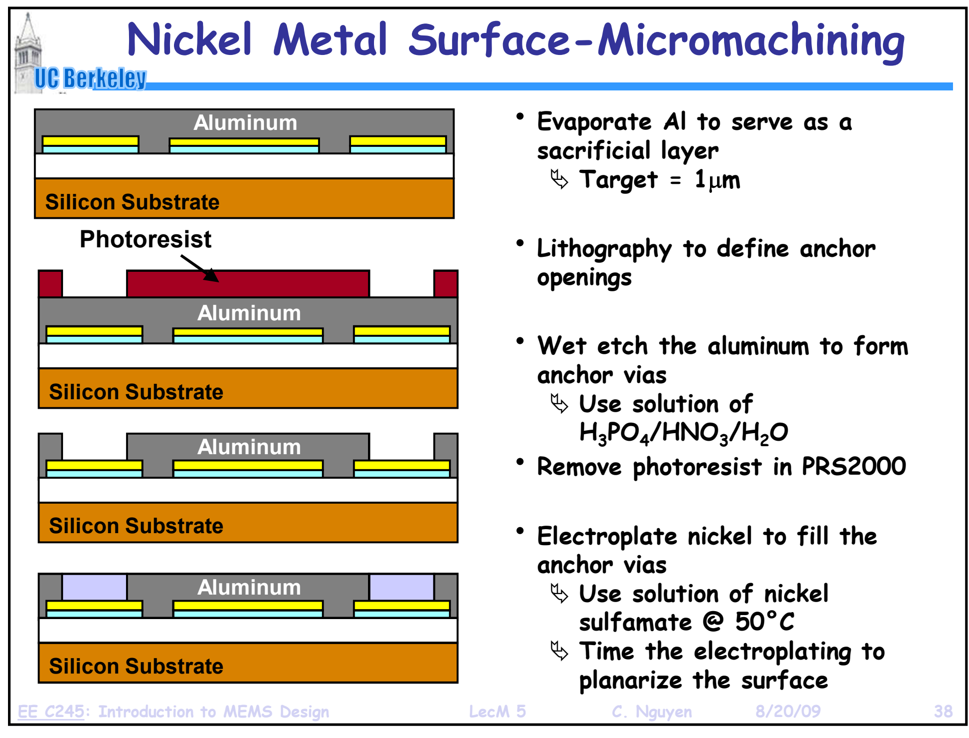

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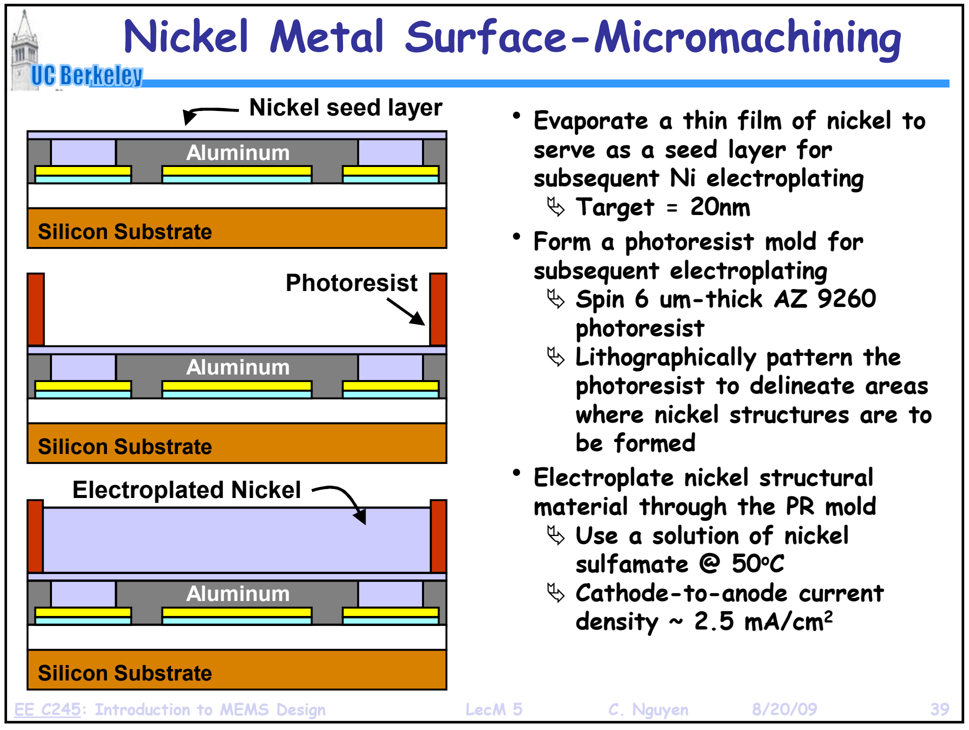

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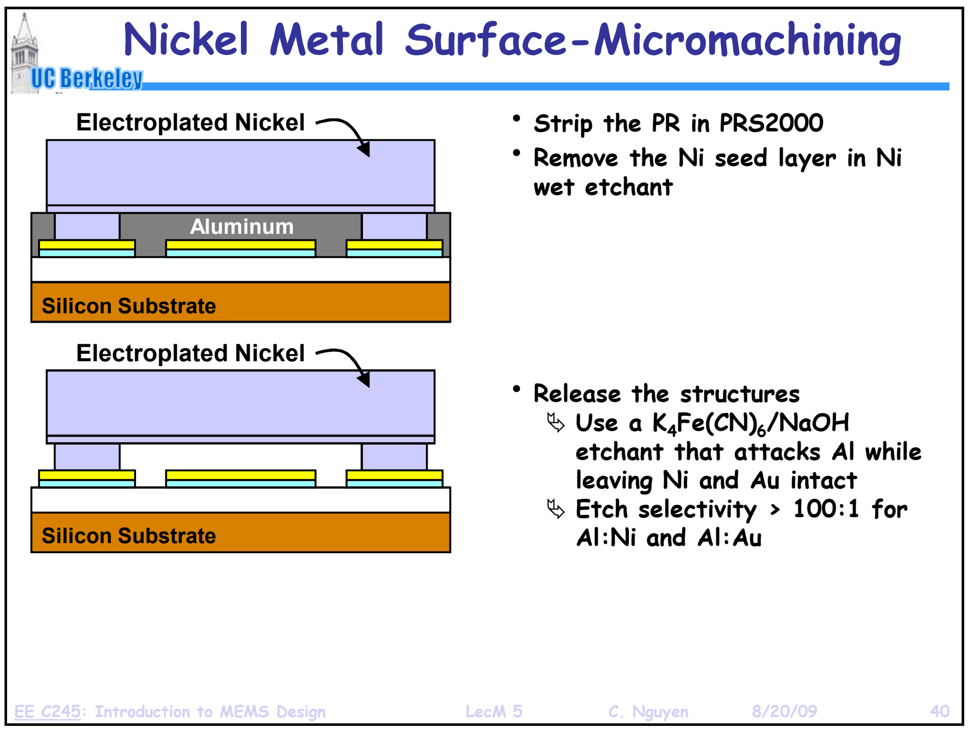

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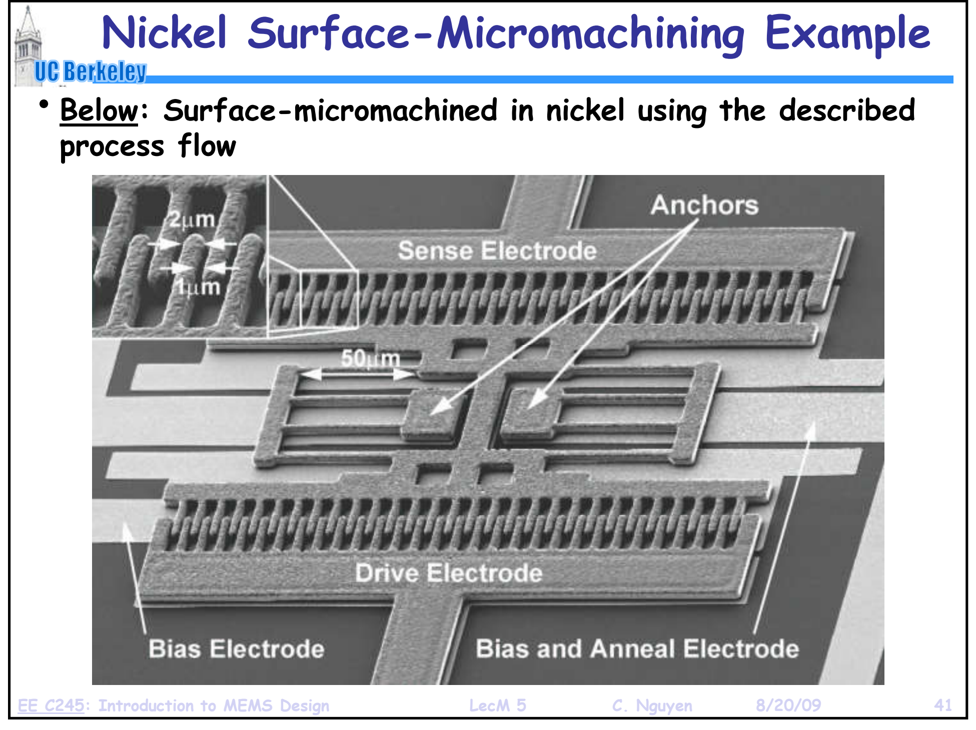

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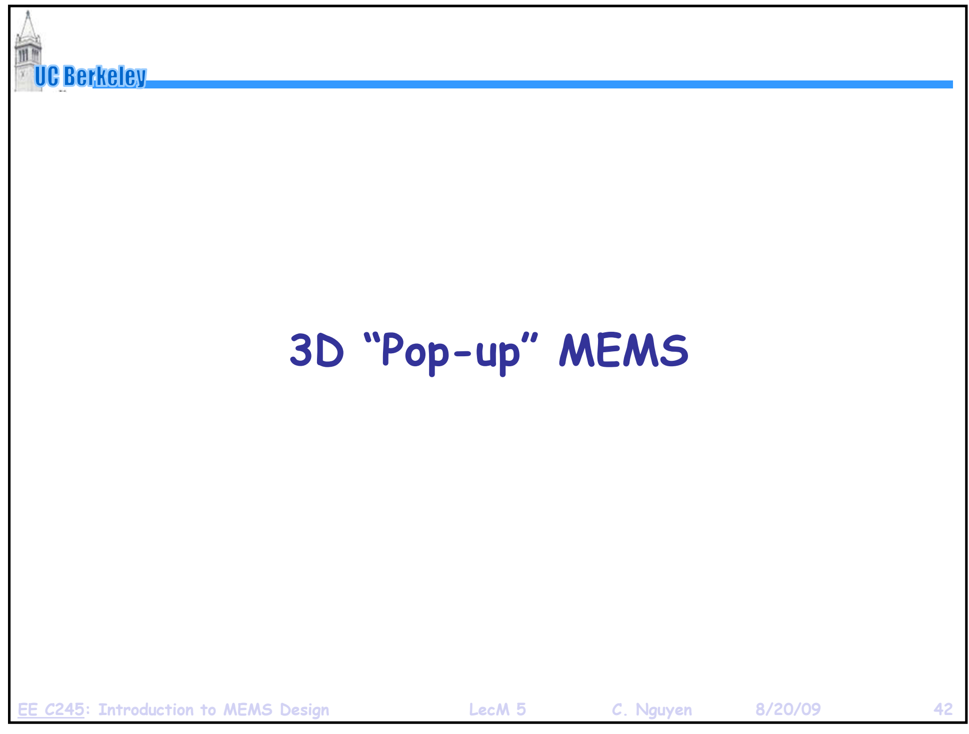

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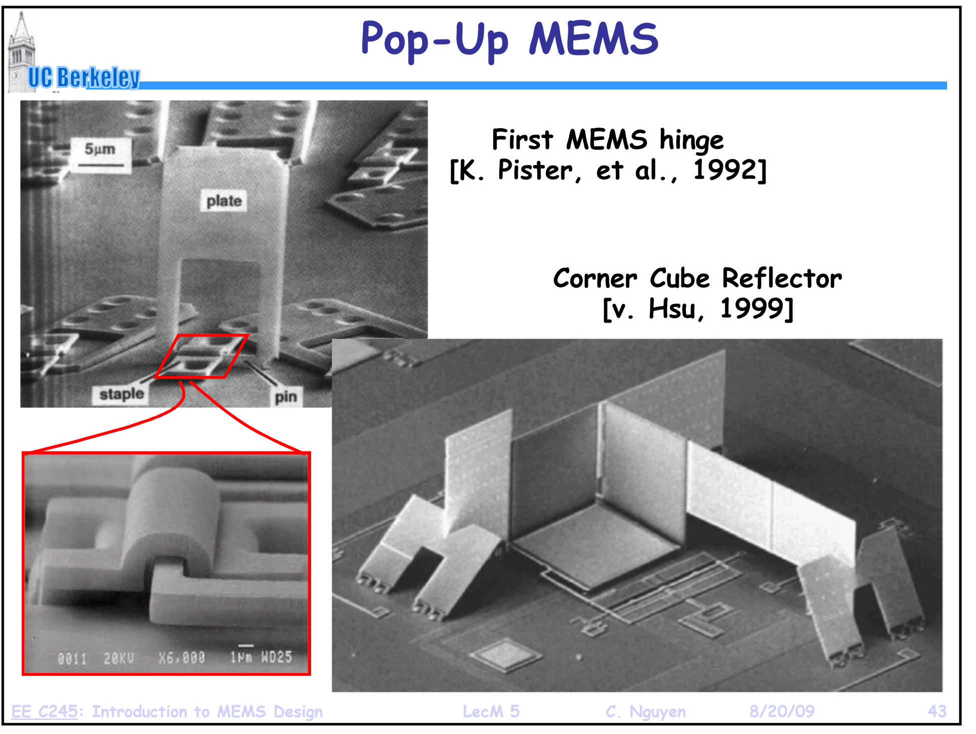

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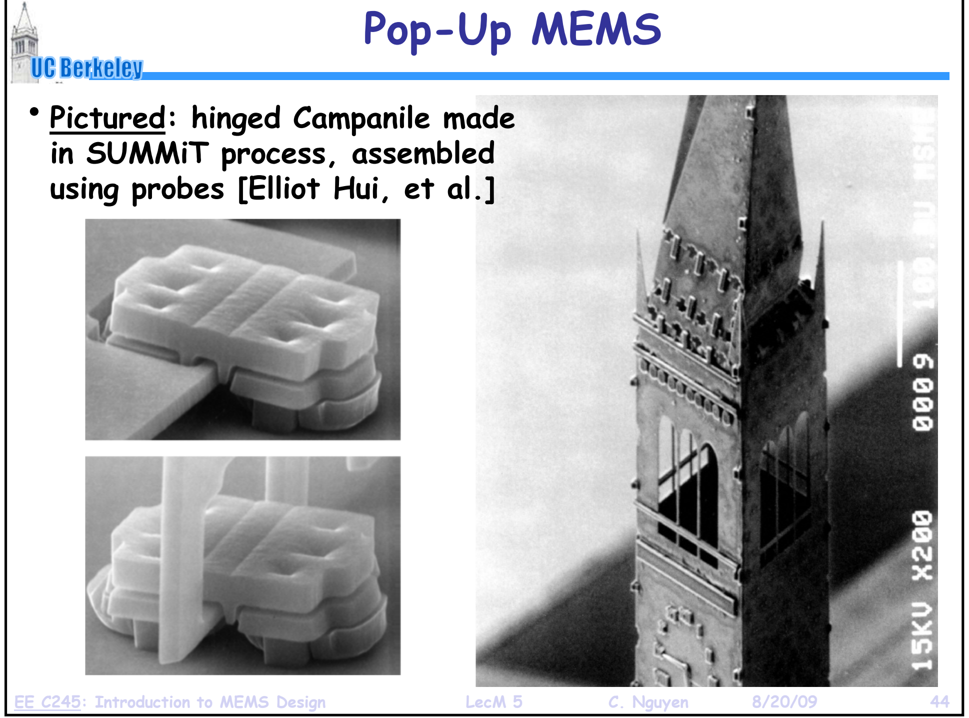

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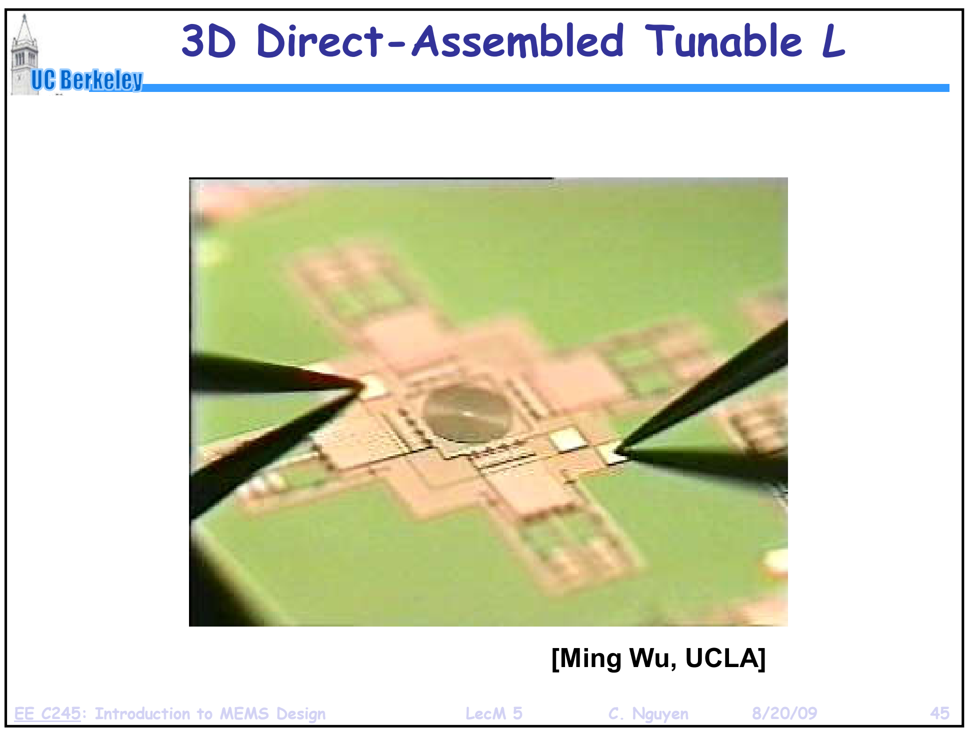

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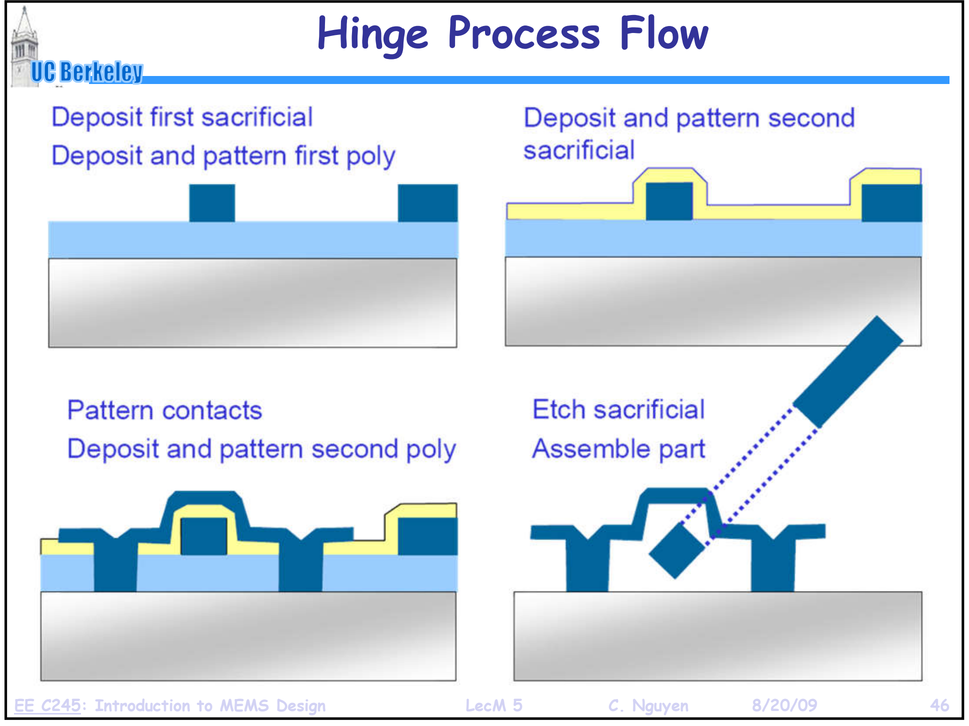

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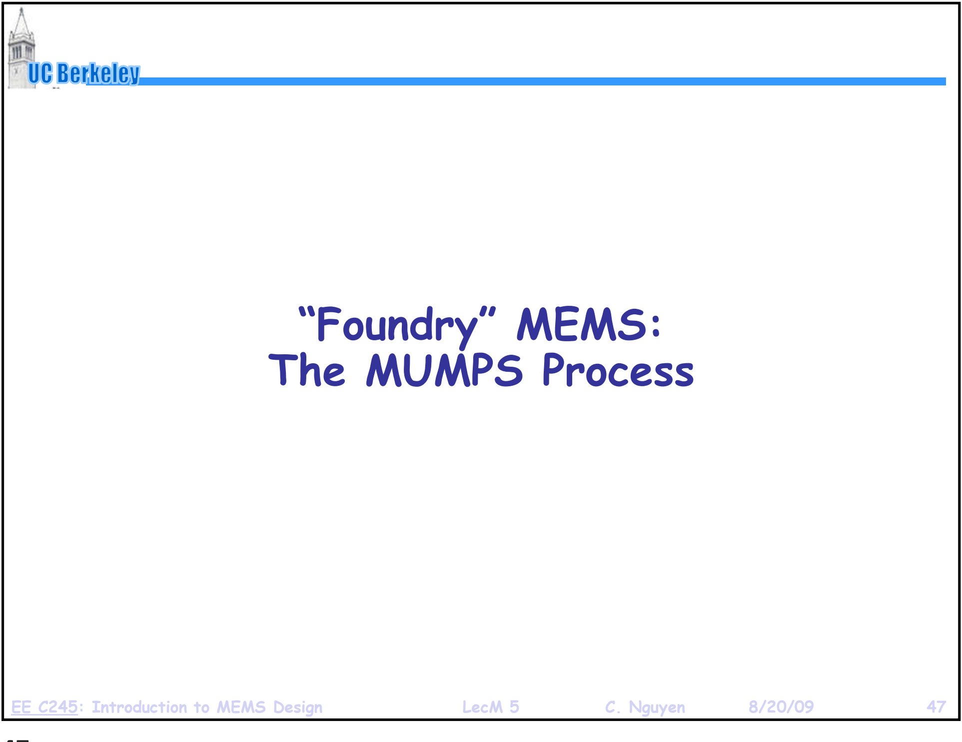

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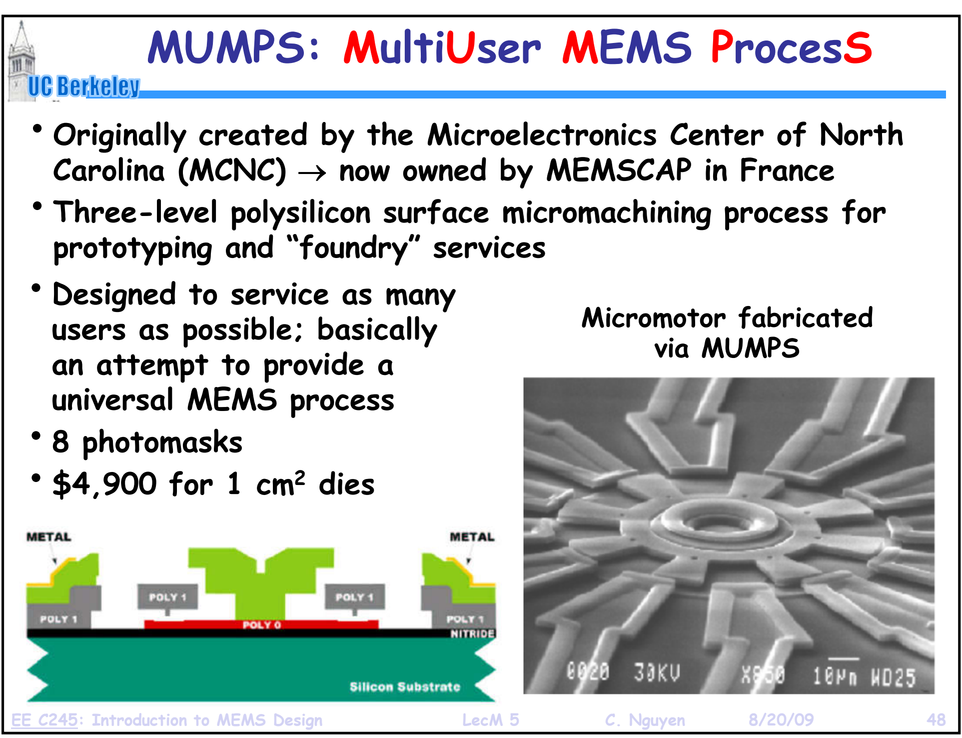

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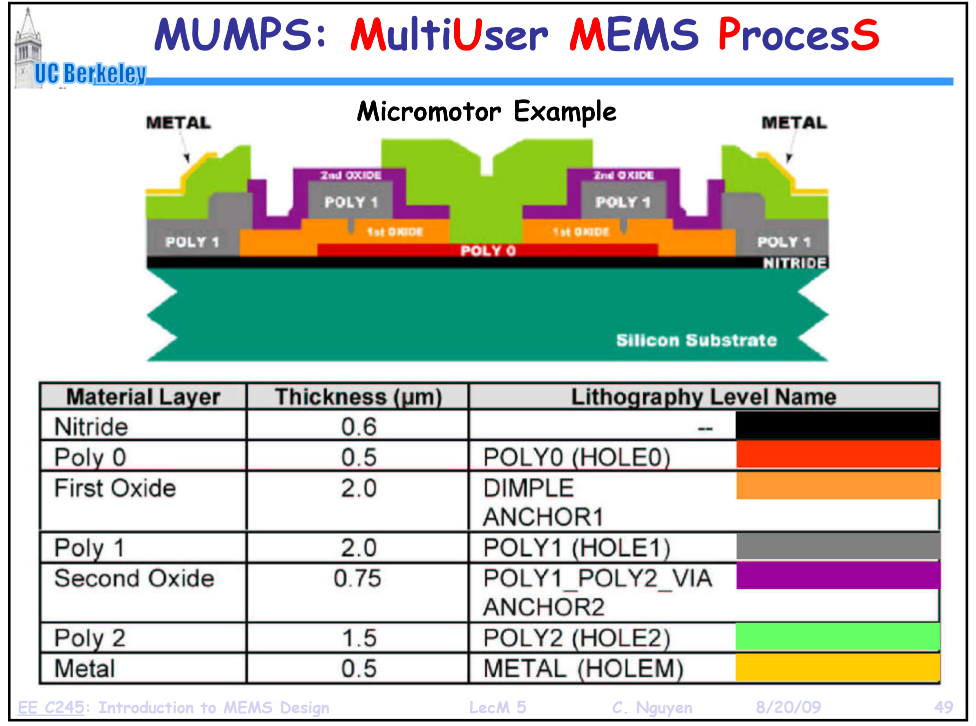

Material Layer	Thickness (µm)	Lithography Level Name
Nitride	0.6	--
Poly 0	0.5	POLY0 (HOLE0)
First Oxide	2.0	DIMPLE ANCHOR1
Poly 1	2.0	POLY1 (HOLE1)
Second Oxide	0.75	POLY1_POLY2_VIA ANCHOR2
Poly 2	1.5	POLY2 (HOLE2)
Metal	0.5	METAL (HOLEM)

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Masks in polyMUMPS

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Minimum set of masks that must be used in MUMPS

Mnemonic level name	Field type	Purpose
POLY0	light	pattern ground plane
ANCHOR1	dark	open holes for Poly 1 to Nitride or Poly 0 connection
DIMPLE	dark	create dimples/bushings for Poly 1
POLY1	light	pattern Poly 1
POLY1_POLY2_VIA	dark	open holes for Poly 1 to Poly 2 connection
ANCHOR2	dark	open holes for Poly 2 to Nitride or Poly 0 connection
POLY2	light	pattern Poly 2
METAL	light	pattern Metal
HOLE0	dark	provide holes for POLY0
HOLE1	dark	provide release holes for POLY1
HOLE2	dark	provide release holes for POLY2
HOLEM	dark	provide release holes in METAL

Extra masks for more flexibility & ease of release

- Field type:
  - Light (or clear) field (cf): in layout, boxes represent features that will stay through fabrication
  - Dark field (df): in layout, boxes represent holes to be cut out

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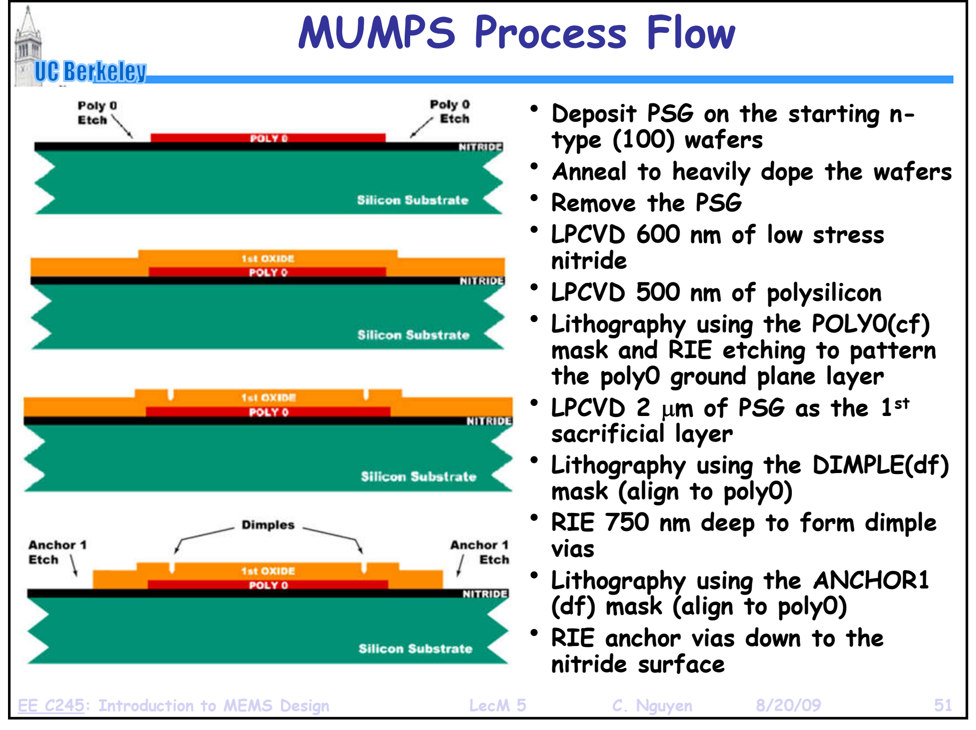

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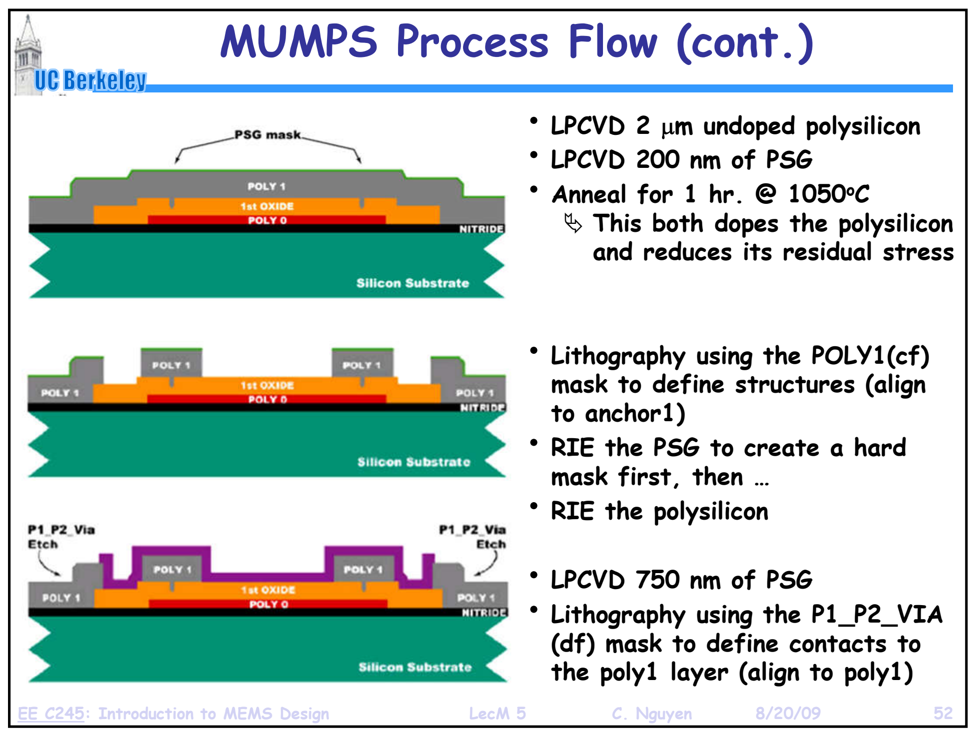

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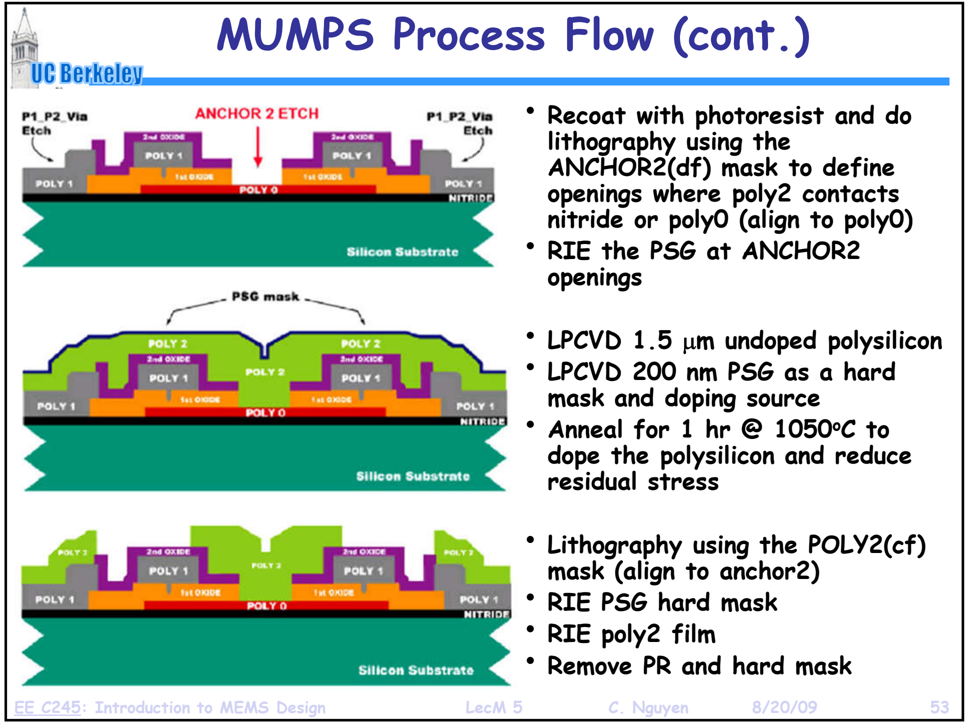

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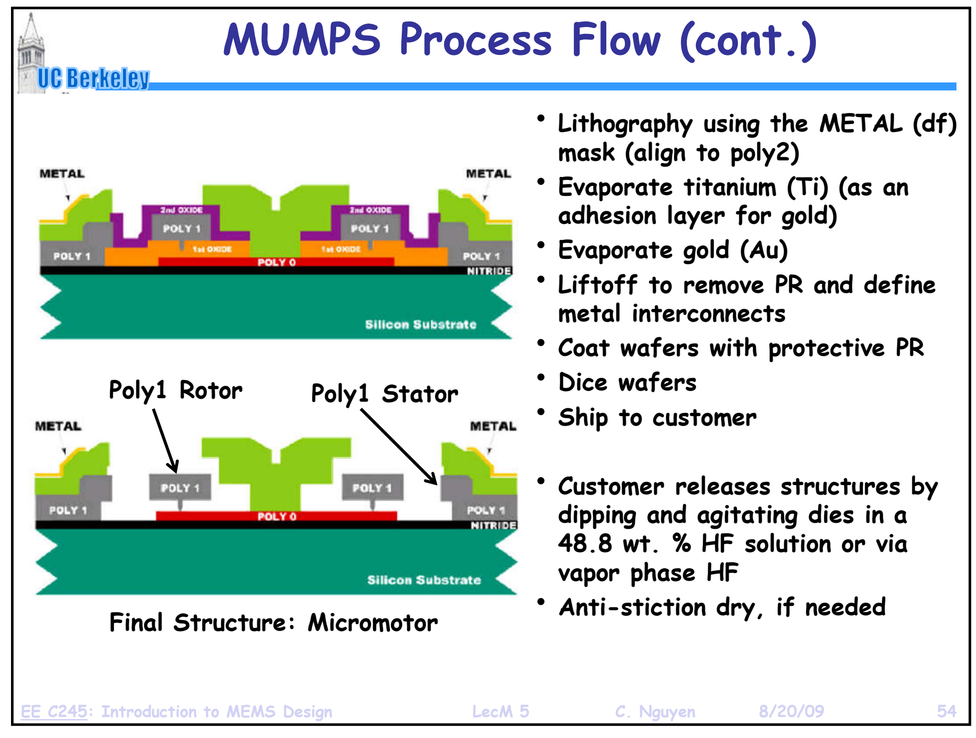

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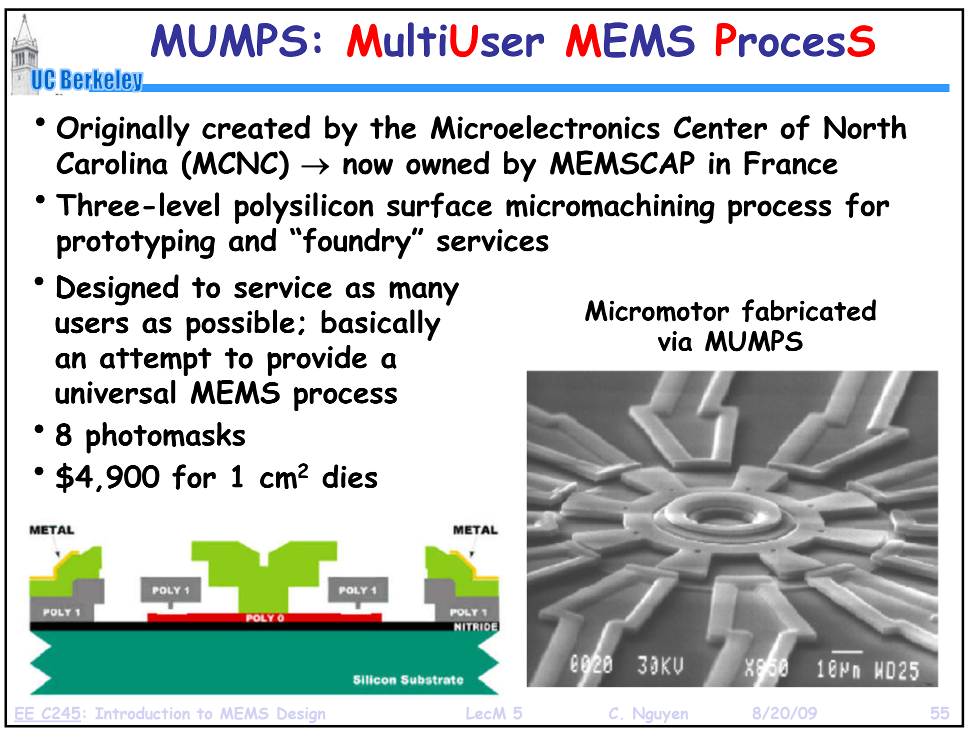

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polyMUMPS Minimum Feature Constraints

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- Minimum feature size
  - Determined by MUMPS' photolithographic resolution and alignment precision
  - Violations result in missing (unanchored), under/oversized, or fused features
  - Use minimum feature only when absolutely necessary

	Nominal [μm]	Min Feature [μm]	Min Spacing [μm]
POLY0, POLY1, POLY2	3	2	2
POLY1_POLY2_VIA	3	2	2
ANCHOR1, ANCHOR2	3	3	2
DIMPLE	3	2	3
METAL	3	3	3
HOLE1, HOLE2	4	3	3
HOLEM	5	4	4

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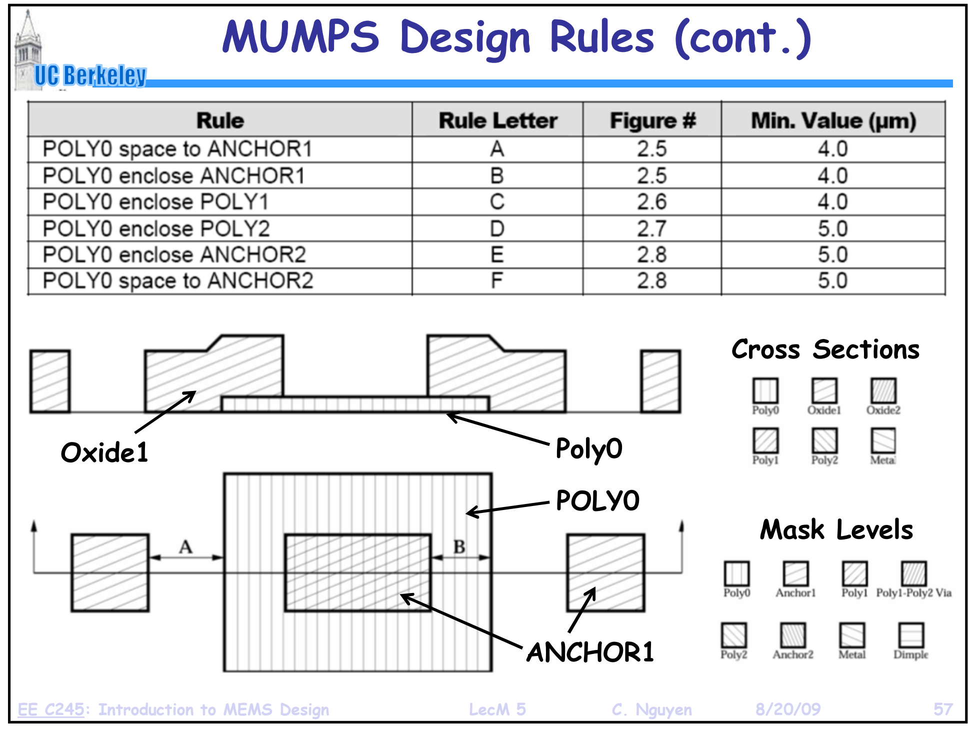

Rule	Rule Letter	Figure #	Min. Value (μm)
POLY0 space to ANCHOR1	A	2.5	4.0
POLY0 enclose ANCHOR1	B	2.5	4.0
POLY0 enclose POLY1	C	2.6	4.0
POLY0 enclose POLY2	D	2.7	5.0
POLY0 enclose ANCHOR2	E	2.8	5.0
POLY0 space to ANCHOR2	F	2.8	5.0

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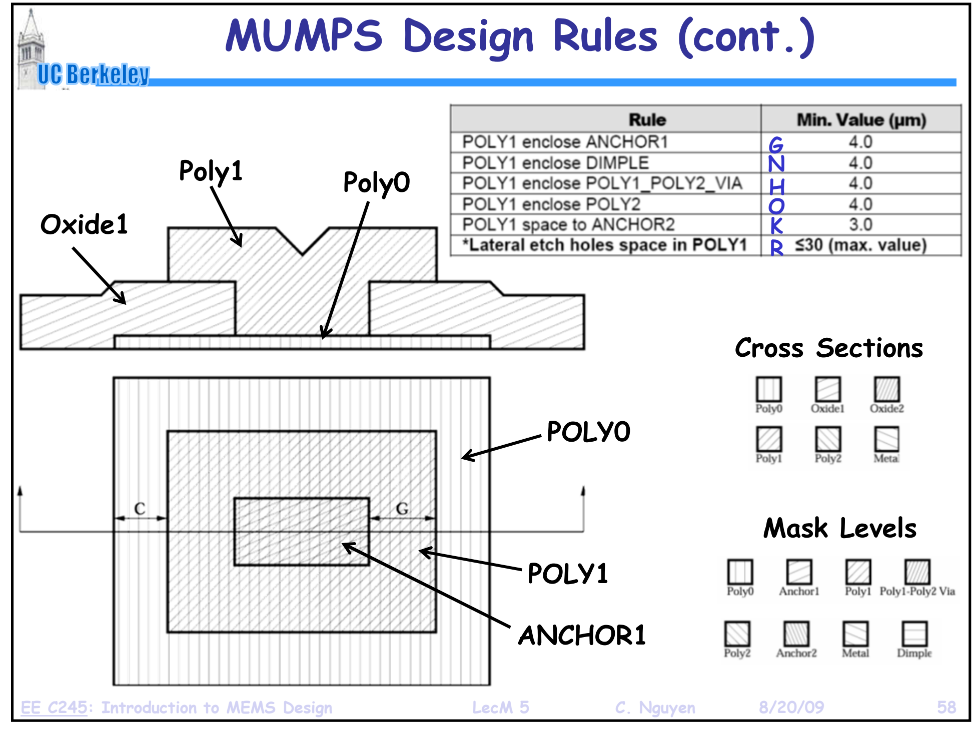

Rule		Min. Value (μm)
POLY1 enclose ANCHOR1	G	4.0
POLY1 enclose DIMPLE	N	4.0
POLY1 enclose POLY1_POLY2_VIA	H	4.0
POLY1 enclose POLY2	O	4.0
POLY1 space to ANCHOR2	K	3.0
*Lateral etch holes space in POLY1	R	≤30 (max. value)

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MUMPS Design Rules (cont.)

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Rule	Rule Letter	Figure #	Min. Value (µm)
POLY0 space to ANCHOR1	A	2.5	4.0
POLY0 enclose ANCHOR1	B	2.5	4.0
POLY0 enclose POLY1	C	2.6	4.0
POLY0 enclose POLY2	D	2.7	5.0
POLY0 enclose ANCHOR2	E	2.8	5.0
POLY0 space to ANCHOR2	F	2.8	5.0

Rule	Rule Letter	Figure #	Min. Value (µm)
POLY1 enclose ANCHOR1	G	2.6	4.0
POLY1 enclose DIMPLE	N	2.13	4.0
POLY1 enclose POLY1_POLY2_VIA	H	2.9, 2.11	4.0
POLY1 enclose POLY2	O	2.14	4.0
POLY1 space to ANCHOR2	K	2.11	3.0
***Lateral etch holes space in POLY1**	**R**	**2.15**	**≤30 (max. value)**

Rule	Rule Letter	Figure #	Min. Value (µm)
POLY2 enclose ANCHOR2	J	2.7,2.10	5.0
POLY2 enclose POLY1_POLY2_VIA	L	2.9	4.0
POLY2 cut-in POLY1	P	2.14	5.0
POLY2 cut-out POLY1	Q	2.14	4.0
POLY2 enclose METAL	M	2.12	3.0
POLY2 space to POLY1	I	2.10	3.0
HOLE2 enclose HOLE1	T	2.16	2.0
HOLEM enclose HOLE2	U	2.16	2.0
***Lateral etch holes space in POLY2**	**S**	**2.15**	**≤30 (max. value)**

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MUMPS Design Rules (cont.)

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Level 1	Level 2	Min. Feature	Min. Spacing	Enclose	Spacing	Cut- In	Cut- Out
POLY0	-	2	2				
	ANCHOR1			4/B/2.5	4/A/2.5		
	POLY1			4/C/2.6			
	ANCHOR2			5/E/2.8	5/F/2.8		
	POLY2			5/D/2.7			
POLY1	-	2	2 / 2.5[2]				
	POLY0						
	ANCHOR1			4/G/2.6			
	ANCHOR2				3/K/2.11		
	POLY2			4/0/2.14			
	DIMPLE			4/N/2.13			
	POLY1_POLY2_VIA			4/H/2.9			
POLY2	-	2	2 / 2.5[2]				
	POLY0						
	POLY1				3/I/2.10	5/P/2.14	4/Q/2.14
	VIA			4/L/2.9			
	ANCHOR2			5/J/2.7			
	METAL			3/M/2.12			
HOLEM	HOLE2			2/U/2.16			
HOLE2	HOLE1			2/T/2.16			

TABLE 2.7. PolyMUMPs design rule reference sheet. Table shows minimum dimensions (µm), rule name, and figure number, respectively.

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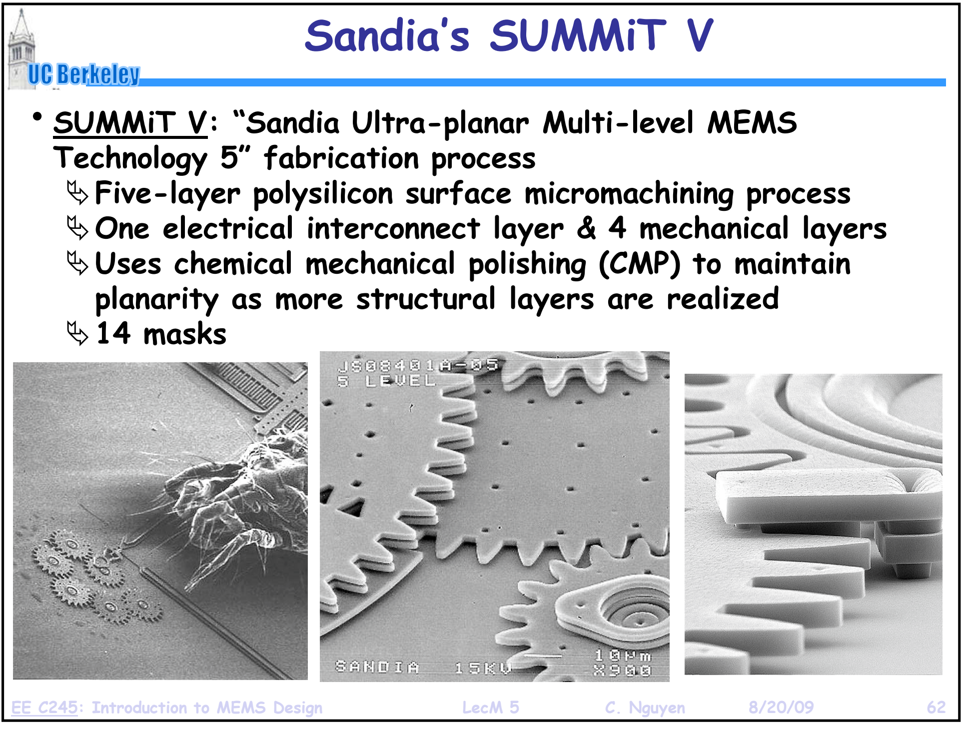

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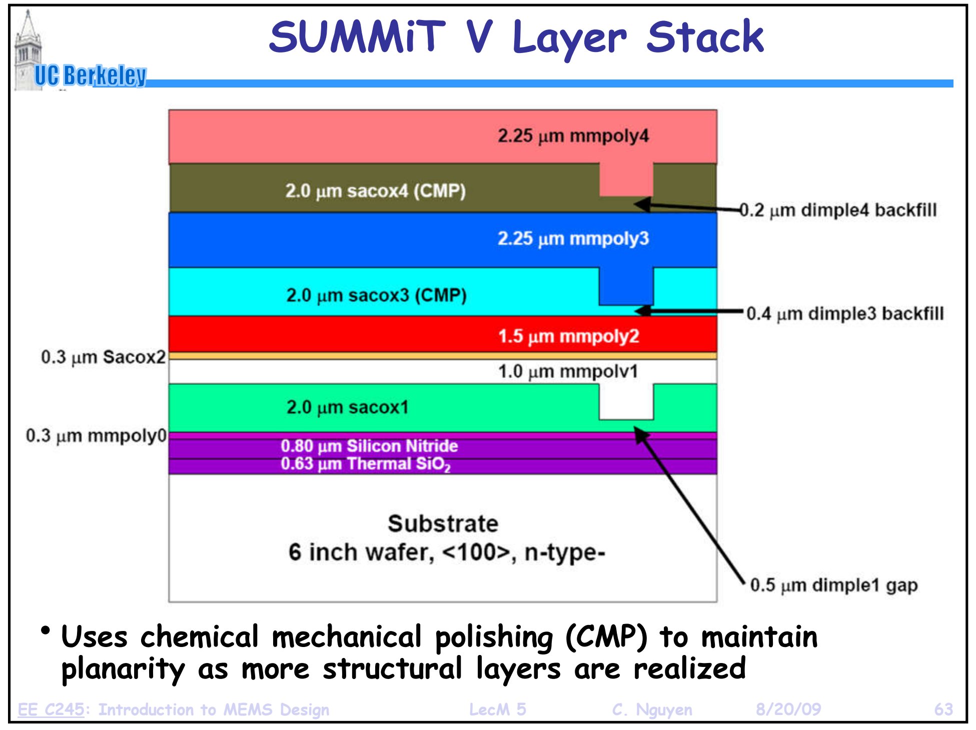

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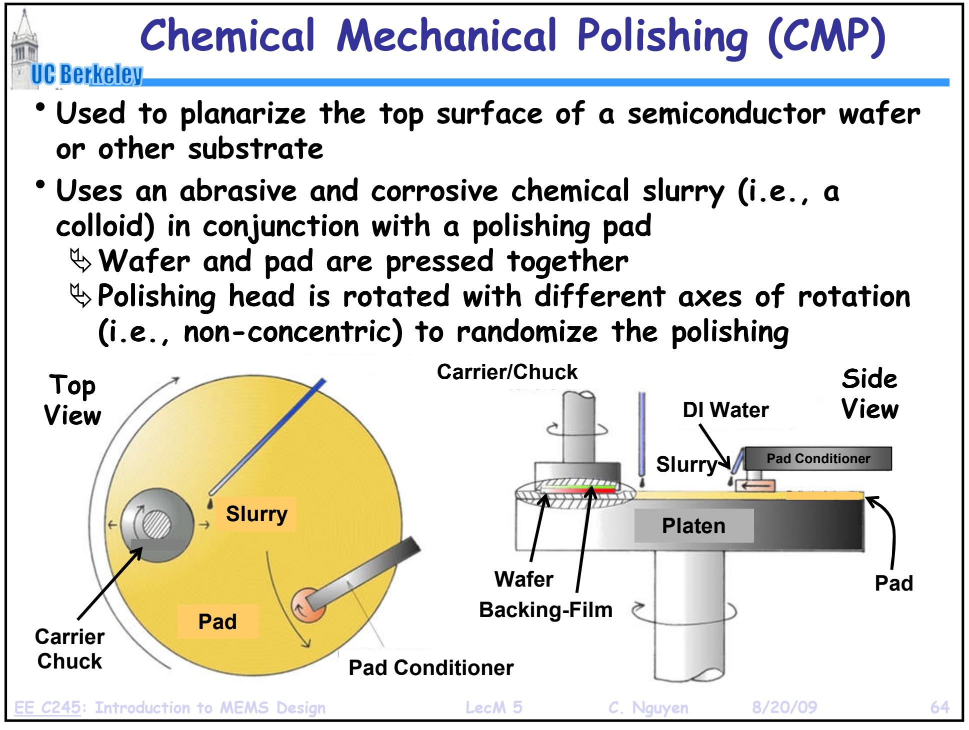

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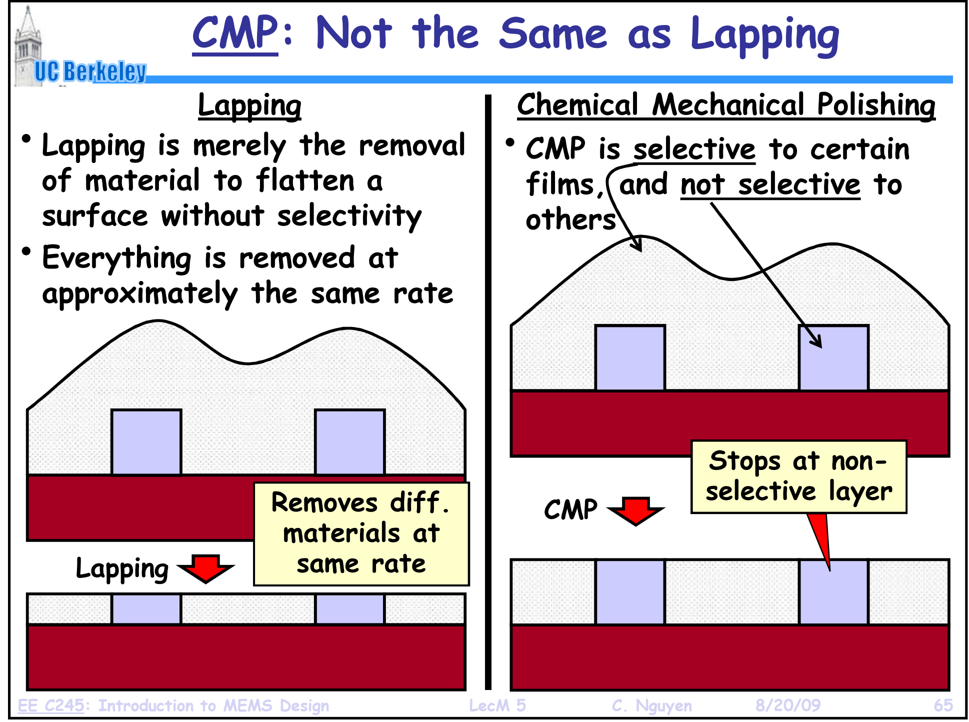

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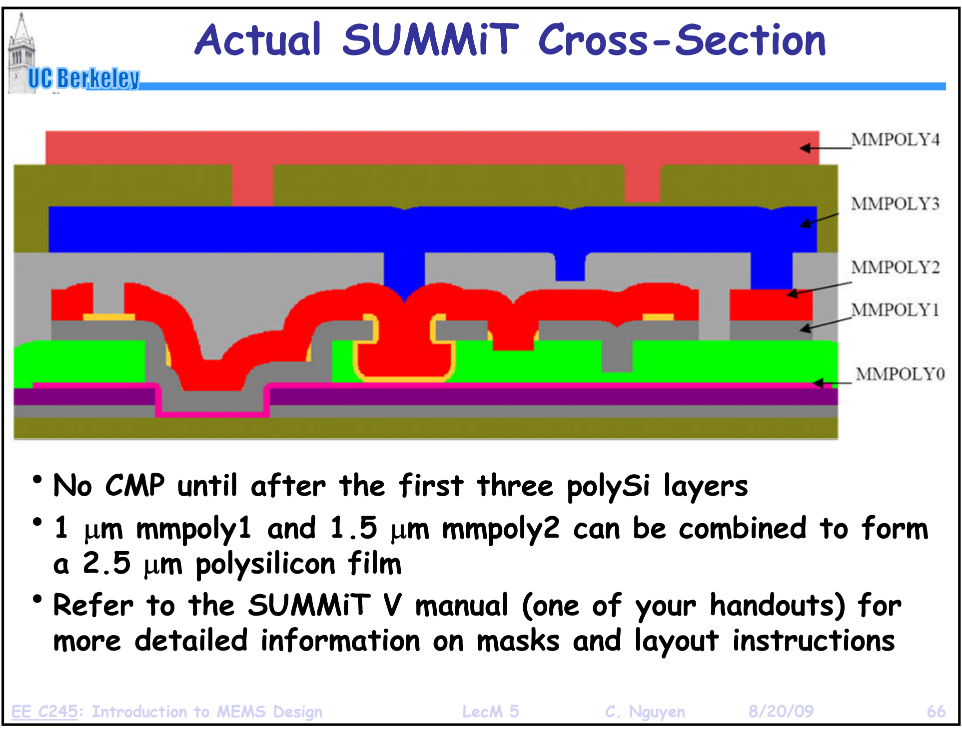

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